RISK ESTIMATING TECHNIQUES FOR UNMANNED SPACE MISSIONS: AN EXPLORATORY STUDY

FINAL REPORT

PRC R-969

19 May 1967

Prepared for

California Institute of Technology
Jet Propulsion Laboratory

By

F. E. Hoffman
G. W. S. Johnson
L. H. Simonsen

PLANNING RESEARCH CORPORATION
LOS ANGELES, CALIFORNIA WASHINGTON, D.C.

RISK ESTIMATING TECHNIQUES FOR UNMANNED SPACE MISSIONS: AN EXPLORATORY STUDY

FINAL REPORT

PRC R-969

19 May 1967

Prepared for

California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Under JPL Contract 951778

By

F. E. Hoffman
G. W. S. Johnson
L. H. Simonsen

PLANNING RESEARCH CORPORATION
LOS ANGELES, CALIF. WASHINGTON, D.C.

FOREWORD

This small analytical study was performed under Jet Propulsion Laboratory (JPL) Contract No. 951778. This effort is, in turn, a subcontract under National Aeronautics and Space Administration (NASA) Contract No. NAS7-100.

The authors wish to acknowledge their indebtedness to the major aerospace companies, such as Atomics International and TRW Inc., who provided data for several spacecraft subsystems. In addition, the authors are appreciative of the efforts of Mr. C. R. Edelsohn in preparing the sections on electrical power and communications. Special credit is given to Mrs. P. Buwalda of JPL and the Voyager Project Support Office for many valuable suggestions for improvements in the risk model.

ABSTRACT

This report presents the results of a small exploratory study on the development of a risk model for unmanned space exploration missions. Risk is defined as the degree of exposure to failure in meeting the program objectives. The model has been calibrated and demonstrated using the Mariner IV mission in 1964 and a future mission using a Mars Orbiter/Lander in 1973 and 1975. The model allows for risk reduction in a multiple-launch program. Various system design candidates and spacecraft subsystem design options can be evaluated to provide quantification of risk with varying inputs. These inputs include schedule, number of spacecraft per launch, number of launches, sterilization intensity, and level of combined system testing.

TABLE OF CONTENTS

LIST OF EXHIBITS

LIST OF EXHIBITS
(Continued)

LIST OF EXHIBITS
(Continued)

I. INTRODUCTION

This document is the final report prepared by Planning Research Corporation and submitted under JPL Contract Number 951778. The study performed under this contract can best be described by listing the major tasks:

1. Develop a risk estimating technique for unmanned space exploration missions, recognizing at least the following:
    a. The risk significance of the loss associated with each concept or action under evaluation.
    b. The significance of the evaluation data as they pertain to the risk involved in decision making.
2. Describe the risk categories and relationships.
3. Demonstrate the use of the risk model on one past mission, Mariner IV, and one future mission, a combined Mars orbiting and landing mission.
4. Perform a sensitivity analysis to determine the importance of various risk categories and parameters.
    a. The risk categories shall include, but not necessarily be limited to, such items as mission design, system design, development/operations, and various subsystems.
    b. The parameters shall include, but not necessarily be limited to, such items as periodic launch schedule and program changes.
5. Refine the previously developed model.
6. Demonstrate the application of the refined risk model by repeating the mission risk examples prepared under 3 above.
7. Prepare a final report showing:
    a. A clear definition and description of all risk categories, relationships, and techniques developed.
    b. Documentation to substantiate engineering judgments and to identify data sources.
    c. Results of the mission risk examples.
    d. A discussion of the scope and accuracy of the risk model.

Using these tasks, a risk model has been developed that allows the assessment of risk for unmanned space exploration missions. Various system design candidates and spacecraft subsystem design options can be evaluated to provide quantification of risk with varying inputs such as schedule, number of spacecraft per launch, number of launches, sterilization intensity, and level of combined system testing.

The model can be used in a multiple-launch program to predict the reduction in program risk with increasing numbers of launches. The model uses postulated failure modes and varying levels of efficiency to diagnose the failures and obtain development fixes prior to the next launch.

II. TECHNICAL DISCUSSION

A. General Approach and Data Sources

The general approach to this small study of risk technique has been to separate the problem into small segments, apply intensive efforts in solving the smaller problems, prepare a preliminary risk model, combine the results, and later calibrate, illustrate, and refine the model. This technique of modeling has been used effectively in the past.

The data sources used are as follows:

1. Open literature on spacecraft design and development
2. Documents on loan from Jet Propulsion Laboratory
3. PRC Spacecraft Data Bank
4. Data obtained from industrial contacts with aerospace firms that are now designing and developing spacecraft

B. Risk Categories and Relationships

Early in the study, the following definition of risk was adopted: Risk is the degree of exposure to failure in meeting the program or mission objectives. The point of view is that of the program manager in a phased procurement of a large space exploration program while the program is still in the early phases, such as those listed below:

Phase A	Advanced Studies, Mission Design, Conceptual Design
Phase B	Preliminary and Initial System Design
Phase C	Contract Definition, Preparation of Detailed Specifications, Costing, and Firm System Design
Phase D_1	Design/Development
Phase D_2	Space Flight Operations

Initially, heavy emphasis was placed on the quantification of development risk by spacecraft subsystems; management and financial risks were to be assessed as additive effects later in the various time phases.

Thus, the risk categories originally were as follows:

1. Spacecraft Subsystem
   Design and Development
   - Structure
   - Propulsion
   - Navigation and Guidance
   - Attitude Stabilization and Control
   - Communications
   - Data Management
   - Electrical Power
   - Descent Systems
   - Experiments
2. Management and Financial Risks

Versus the Major Time Phases

With this framework of risk categories in mind, the risk estimating relationships for any spacecraft subsystem design and development were to be developed from an appropriate performance parameter plotted versus time. The risk function was then to be calculated from the parameter plot in the manner shown in Exhibits 14, 15, and 16 (see pages 38, 39, and 40).

C. Preliminary Risk Model

A preliminary risk model was prepared and displayed in Reference 1. An inspection of this report shows four major risk categories: System Design, Spacecraft Subsystem Design and Development, Combined Systems Testing, and Space Flight Operations.

In preparing this preliminary model, a decision was made to quantify risk independent of cost and to include schedule as a management risk under mission design. This decision allows trades to be made between schedule, risk, and system design alternatives using this report. Trades between schedule, cost, and the same system design alternatives can be made using the cost model shown in Reference 2.

D. Final Risk Model

The final risk model is now presented in four major time phases of a typical unmanned space exploration mission.

1. Mission Design

Within this time phase, the mission design activity involves establishing mission objectives, defining payload requirements, selecting a launch vehicle, synthesizing system design candidates, performing system design, performing trajectory calculations, selecting an operational mode, establishing hardware and contractual interfaces, defining long-leadtime development items, establishing funding plans, and defining subsystem design and development options. In order to define mission design risk, these activities are grouped under four subcategories as shown in Exhibit 1. The system design candidates, DC_1, DC_2, and DC_i, are considered inputs and would be evaluated separately as alternatives.

The schedule risk versus development time is shown in Exhibit 2 and is an engineering judgment based on experience and recent perusal of five unmanned space exploration programs. The nominal development time, N, is the number of years to perform the Phase D development effort under system management. Phase D time spans for a major program could be 3 to 4 years under system management or 2 to 3 years under laboratory management with considerable inherited development.

Technological innovations in nonspacecraft system elements are rare. Although the launch vehicle is usually an inherited development from another program and is already qualified by many successful space flights, it is possible to visualize several examples of nonspacecraft innovations that could be utilized in a large space program:

a. A new high-energy upper stage in the launch vehicle;
b. A new larger antenna in the deep space net (DSN);
c. A new shroud (adapter) between the launch vehicle and the spacecraft.

By definition, a technological innovation refers to a major space system element that has passed feasibility tests on the ground and may have successfully flown in one or two space flights, yet lacks sufficient operational experience to be quantified as a mature technology.

Exhibits 3 and 4 have been prepared to quantify the risk of nonspacecraft technological innovations versus successful test experience for no backup development and one backup development per innovation. These curves are based on engineering judgment, and the risk with one backup development per innovation is based on the premise that both developments are equal in risk.

Frequently, the selection of an operational mode early in the mission design phase leads to difficulties later, either in the design and development phase or in the space flight operations phase. This risk can be called the operational mode complexity risk and is visualized as a function of guidance accuracy required, communications distance, and the number of separable but related modules. Exhibit 5 shows operational mode complexity risk versus guidance accuracy required in terms of miss distance from an aiming point near the planet to be explored. The curves were developed using engineering judgment and data from References 3 and 4. The influence of communications distance and the number of separable but related modules on this risk is left to the judgment of the reader.

The mission design risk is then summarized as follows:

$$\text{Risk}_{MD} = 1 - (1 - \text{Risk}_{S})(1 - \text{Risk}_{TI})(1 - \text{Risk}_{OM})$$

where the subscripts refer to schedule, nonspacecraft technological innovations, and operational mode complexity, respectively.

2. Spacecraft Subsystem Design and Development

The risks encountered in the spacecraft subsystem design and development phase are shown in Exhibit 6 and can be segregated into two subcategories: the risk in developing technological innovations and the risk in developing subsystems based on mature technologies validated by substantial space flight experience. Exhibits 7 and 8 are used to quantify the risk in developing spacecraft technological innovations; the risks for developing mature subsystems are shown in Exhibits 9 through 27.

Exhibits 7 and 8 refer to spacecraft technological innovations. A technological innovation is defined here as a major spacecraft subsystem that has passed feasibility tests on the ground and may have flown in one or two space flights, yet lacks sufficient flight experience to qualify as a mature technology. The technological risk is plotted versus a test experience factor, T , for various numbers of innovations, I .

Typical examples of spacecraft technological innovations are nuclear electric propulsion, solar-heated hydrogen rocket, and gravity gradient stabilization in synchronous orbit.

a. Structure

Exhibits 9 through 13 have been prepared to estimate the risk for spacecraft structure design and development. Exhibit 9 was calculated using the method of Gerard, Reference 5, and Exhibits 10 and 11 are taken directly from Reference 6. Exhibits 12 and 13 on ballistic entry spacecraft structure are largely calculated from data in References 7 and 8.

b. Propulsion

The propulsion parameter, Exhibit 14, is based largely on data from the PRC Spacecraft Data Bank and References 9 and 10. The performance values are plotted for both solid and liquid rockets as total impulse/stage weight versus time in years. With the simplifying assumption of constant thrust, this performance value can be assessed in several ways:

$$\frac{I_t}{\text{Stage Weight}} = \frac{\text{Thrust x Burning Time}}{\text{Stage Weight}} = \frac{I_{sp}}{1 + \frac{W_E}{W_p}}$$

where I_{sp} = specific impulse (seconds)

W_E = stage empty weight (pounds), including structure and rockets but excluding payload or adapters

W_p = weight of propellants (pounds)

Two curves are shown, one for launch vehicles and larger, separable spacecraft propulsion modules, and the other for spacecraft propulsion.

The subsystem performance values shown can now be used to construct risk functions. For example, the propulsion subsystem performance value (impulse/stage weight versus time in years) is used to illustrate the methodology. Considering subsystem development risk as a third dimension normal to the plane of the paper in Exhibit 15, we can take a cross plot at any future date, say 1977 (Section A-A of Exhibit 15), and construct the risk function as shown in Exhibit 16. Thus, the risk function becomes a three-dimensional surface on a plot of subsystem performance value versus time.

c. Navigation and Guidance

The performance parameter selected for navigation and guidance was

$$\text{Performance Parameter} = \frac{1}{\text{Miss Distance x Weight}}$$

The miss distance is defined as the distance from an aim point in space near the planet to be explored. The weight is the navigation and guidance subsystem weight.

Exhibit 17 presents the performance parameter versus calendar year for past JPL spacecraft programs. These data were taken from Reference 11. Data for the lunar vehicles and Mariner II were scaled to Mars 1964 by the relationships of Reference 11, i.e., a 1-microsecond velocity increment in the most sensitive direction can change a lunar trajectory about 200 km, a 1964 Mars trajectory 20,000 km, and the 1962 Venus trajectory about 10,000 km. This exhibit is for one midcourse correction; additional midcourse corrections would yield a different curve.

d. Attitude Stabilization and Control

The performance parameter selected for the attitude control was

$$\text{Performance Parameter} = \frac{1}{\text{Angular Deviation x Weight}}$$

Two cases are presented in Exhibit 18: the system constrained by the limit cycle and the system in the gyro hold mode.

Exhibit 18 presents data for three past programs, Mariners II and IV and Surveyor, and two contractor proposed programs, Lunar Orbiter applied to Mars and an Avco Voyager study (see References 13 through 16). Each data point is for the one sigma value of the angular deviation. All systems were cold gas systems.

e. Communications

Analysis of the risk of space communication system development has been carried out based on development of a suitable measure of communication system performance tradeoffs and available historical information describing the performance of past systems. The measure of performance has been reduced to a single equation relating information rate, distance, and weight:

$$P = \frac{\text{Information Rate (bits per sec)} \times \text{Range}^2 \text{ (n. mi.)}}{\text{Weight (lbs)}}$$

This equation includes the most important characteristics while avoiding the complexities of a more involved formulation. The communications subsystem performance parameter is plotted in Exhibit 19.

The historical data used in obtaining the data points have been obtained from various JPL and NASA reports and from major aerospace contractors. The data sources are References 17 through 22.

f. Data Management

The heart of a data management system is the computer. Data are presented based on a PRC survey study of spaceborne computers, Reference 23. Exhibits 20 and 21 present these data in two different forms--bits per microsecond per unit density (lbs/ft^3) and bits per microsecond per pound. The addition time was used to determine the processing capability in bits per microsecond. These data have a large degree of scatter, and, in keeping with the philosophy of risk being greatest when the state of the art is exceeded, the curves are drawn at the upper bound of performance.

g. Electrical Power

The analysis of the risk involved in space power system development has been based on two types of information, both contained in the open literature. The first category includes survey articles and papers in the field of space power which examine the state of the art at a particular time. Included in this category are books such as those by Sego and Snyder which survey the field. The second category includes reports such as those by JPL which provide great detail on a particular space system or spacecraft.

These sources of information, References 24 through 32, have been combined to form the various charts relating to the growth of the electrical power system capability as a function of time. The parameter chosen as a measure of capability is:

$$\frac{\text{Power Level (kw)} \times \text{Lifetime (hrs)}}{\text{Weight (lbs)}}$$

This parameter was chosen as a measure of total energy (the required output) compared to weight (the resulting penalty). The electrical power data have been plotted in Exhibits 22 through 25.

h. Descent Systems

A descent system is defined as the means for decelerating a spacecraft as it approaches a planetary surface. Specifically, for the operation in the atmosphere of a remote planet, a large parachute will provide the initial deceleration upon entering the atmosphere. The final touchdown on the surface will usually be accomplished with throttleable rockets.

Since a parachute is a deceleration device, the design objective is to maximize the drag force, D_F. However, due to the problem of transporting the parachute to the vicinity of the planet, another objective is to minimize the weight. Thus, the overall objective of the descent system designer is to maximize the ratio D_F/W_p. But

$$D_F = q C_D A_o = \frac{1}{2} \rho v^2 C_D A_o$$

where D_F = drag force (pounds)

q = stagnation pressure (lbs/ft^2)

C_D = coefficient of drag

A_o = drag area = $\pi D^2/4$ (D = maximum diameter of parachute)

ρ = atmospheric density (slugs/ft^3)

v = velocity at start of opening (ft/sec)

W_p = weight of parachute system (pounds)

Therefore,

$$\frac{D_F}{W_p} = \frac{q C_D A_o}{W_p} = \frac{\rho v^2 C_D A_o}{2W_p}$$

Let

$$m = \frac{W_s}{g}$$

where m = mass of weight suspended (lbs-sec^2/ft)

g = acceleration of gravity (ft/sec^2)

W_s = total weight in earth pounds of suspended system including W_p (pounds)

Dividing both numerator and denominator by m,

$$\frac{D_F}{W_p} = \frac{\rho v^2 \dfrac{C_D A_o}{m}}{2 \dfrac{W_p}{m}} = \frac{\rho v^2 \dfrac{C_D A_o}{m}}{2g \dfrac{W_p}{W_s}} = \frac{q}{g \dfrac{W_p}{W_s} \dfrac{m}{C_D A_o}}$$

This last expression permits use of the ballistic coefficient, $m/(C_D A_o)$, and the ratio of the weight of the parachute system to the total suspended weight.

The foregoing parameter, D_F/W_p, has been plotted in Exhibit 26 against calendar time for several descent systems of the type expected to be applicable to the Martian environment. It can be seen that a technological improvement has occurred when the spacecraft parachutes are compared to the standard 28-foot chute used by the Air Force. Exhibit 26 also shows the results of some high-altitude tests (138,000 feet above Mach 1) of a deceleration system being developed for the Martian mission. It can be seen that the tests are well below the expected capability. The exhibit also shows that the next tests anticipate an order-of-magnitude improvement over the first test; however, additional development effort will be required to increase the performance value to the state of the art as shown.

i. Experiments

The risk of designing and developing many diverse experiments has been quantified by the use of an operational maturity index (OMI) as shown in Exhibit 27. The risk of the ith experiment is obtained as follows:

$$R_{EXP_i} = 1 - \frac{(OMI)_{Demonstrated}}{(OMI)_{Required}}$$

To obtain the overall experiment-development risk, the following relationship is used:

$$R_{EXP} = \sum_{i=1}^{i=n} \frac{WR_i}{n}$$

with a weighting factor of $w = 2$ for major experiments and $w = 1$ for minor experiments, and n = number of experiments.

In this case, an experiment is classed as a major experiment if the weight exceeds one-third the payload.

To summarize for the spacecraft subsystem design and development phase, the risk is obtained as follows:

$$Risk_{SBD} = 1 - (1 - R_{STI})(1 - R_1)(1 - R_2)(\cdots)(1 - R_9)$$

where STI = spacecraft technological innovations
Subscript 1 = structure
2 = propulsion
3 = navigation and guidance
4 = attitude stabilization and control
5 = communications
6 = data management
7 = electrical power
8 = descent system (parachutes)
9 = experiments or mission sensors

3. Spacecraft Combined Systems Testing

The combined systems testing risk was judged to be a function of four risk categories (Exhibit 28):

a. Environmental knowledge of the planet
b. Sterilization intensity
c. Subsystem interaction
d. Module interaction
e. Test plan

The combined systems testing risk is largely subsystem interaction risk and module interaction risk as opposed to the subsystem level testing risk which is a part of design and development (subsection II.D.2).

a. Environmental Knowledge Risk

One of the fundamental problems in testing is the specification of the test environment. In the case of space exploration, as planetary data are gathered the knowledge of the environment will be enhanced. This environmental knowledge will result in a reduction of the testing risk, i.e., the risk that testing is performed to the wrong environmental specification. Exhibit 29 presents this risk as a function of the level of knowledge of the environment near a planet. Engineering judgment and careful calibration to the Mariner IV flight was the technique used for the determination of Exhibit 29.

b. Sterilization Intensity Risk

The risk due to sterilization is a function of sterilization intensity--namely, time and temperature. For purposes of this study, intensity is defined as the sterilization temperature for 30 hours. The risk estimation curve, Exhibit 30, is based on engineering judgment backed by typical electronic subsystem performance degradation curves as shown in Reference 12, page 341.

c. Subsystem Interaction Risk

Interaction risk is a function of the percentage of engineering effort for a particular module devoted to system testing and simulation. At the individual module level, the interaction risk is a function of the number of technological innovations per module, as shown in Exhibit 31. This risk primarily reflects the influence of each subsystem on the other subsystems.

d. Module Interaction Risk

The interaction risk of one module on others is shown in Exhibit 32 as a function of the number of modules and level of module integration testing. In this relationship, the level of module integration testing is expressed as a percentage of the total engineering effort for all modules.

e. Test Plan Risk

The test plan risk, Exhibit 33, indicates the risk involved in not planning for adequate simulation of the desired test conditions. For example, interplanetary spacecraft are frequently launched without any prior low-earth-orbit testing; test policies such as this can save time and money under certain circumstances, but increase the risk. The test plan risk is derived from the following relationship:

$$R_{TP} = 1 - \frac{\text{Test Experience Index Demonstrated}}{\text{Test Experience Index Required}}$$

This relationship should be summed for each major module--propulsion, spacecraft, and capsule--along with major experiment subsystems, such as an Automated Biolgical Laboratory. Risk is therefore given by:

$$R_{TP} = \frac{1}{n} \sum_{n=1}^{n} \left(1 - \frac{TEID}{TEIR}\right)$$

where n = the number of modules plus major experiment subsystems

For the combined systems testing phase, the risk can be summarized as follows:

$$R_{CST} = 1 - (1 - R_{ENV})(1 - R_{SI})(1 - R_{I})(1 - R_{M})(1 - R_{TP})$$

where ENV = environmental
SI = sterilization intensity
I = subsystem interaction
M = module interaction
TP = test plan

4. Space Flight Operations

The space flight operations risk was judged to be a function primarily of the risk due to interplanetary mission time and the number of major events or maneuvers the spacecraft is required to execute during a mission. The latter was designated as the risk due to changes of state in space flight operations and is also influenced by the number of spacecraft per launch. This relationship is depicted in Exhibit 34.

Other potential risk categories within space flight operations were examined but, for one reason or other, were eliminated in the final model. The risk due to mission training deficiencies was one of these. It was eliminated for two reasons: quantification difficulty due to lack of historical data of past programs, and the intuitive judgment that the mission training risk was minimal.

The environmental risk was originally allocated to space flight operations but later transferred to the category of combined systems testing. The decision to transfer this risk to combined systems testing was based on the judgment that the real environmental risk in that spacecraft is designed and tested to the wrong environment. Rather than double counting of the risk by having it in both subsystem design and combined testing, environmental risk was placed within combined systems testing.

a. Mission Time

The risk as a function of mission time is given by Exhibit 35. The calibration of the mission risk curve with time was based on Mariner IV, where the flight time was approximately 225 days. The judgment exercised was that the mission time risk was small for this flight time. Extrapolation of the Exhibit 35 curve beyond 225 days was based on engineering judgment. With longer flight time of subsequent missions, the extrapolation can be refined. Medium-altitude earth satellite vehicles with flight times longer than 225 days would probably have some merit as extrapolation points. These data were not gathered in this study due to limited resources.

A standard reliability approach using part failure rates was deemed inappropriate in this study for the mission time risk. In the mission/project phase, no design detail is available to utilize this approach. One may begin to use this approach as hardware is designed and developed and as the program progresses.

b. Changes of State

A change of state is defined as a major event or maneuver the spacecraft must perform during the mission. The model includes the launch as a change in order to allow later estimation of program risk. A typical scenario by changes of state is launch, injection, spacecraft separation, midcourse correction (1 through n), retrofire near planet, circularize orbit, separate capsule, deorbit capsule, capsule entry, touchdown, and lander operations. Events of lesser significance, such as radio commands, power switch on and off, etc., were not considered changes of state.

Exhibit 36 presents the risk due to changes of state versus the number of changes of state for cases of one and two spacecraft per launch. This type of presentation avoids a detailed scenario breakdown which is an alternate method of presenting this risk. In other words, one could have along the abscissa of Exhibit 36 for $N = 1$, launch, $N = 2$, injection, and $N = 3$, first midcourse correction, etc. An incremental risk for each change of state could be assigned and a curve constructed for each scenario. Generality was desired for this study since interplanetary scenarios have a wide degree of flexibility; therefore, the more general method of presentation was selected. Given the number of changes of state, Exhibit 36 gives change of state risk directly.

For the one spacecraft per launch case, the relationship chosen for this risk was $R = 0.01\ N^{1.3}$, where N = number changes of state. The constant, 0.01 , calibrates the change of state risk. This formulation recognizes the higher risk associated with the change of state near the remote planet. As the number of changes of state increases, the mission in general will be more complex with each additional one, adding a greater increment of risk than the previous one. This rationale was the basis of the formulation. The curve was calibrated to Mariner IV which had five changes of state: launch, injection, separation, midcourse correction, and television camera pointing. The two spacecraft per launch vehicle or dual launch case is different in that the risk is common to both spacecraft prior to spacecraft separation, but peculiar to each spacecraft subsequent to separation. Exhibit 36 presents a diagram of the change of state risk for the dual launch while Exhibit 37 shows typical changes of state for this case. Exhibits 36 and 37 reflect the fact that the spacecraft are separated after injection at $N = 2$, i.e., after launch and interplanetary injection.

The change of state risk for the case of multiple spacecraft per launch is given by:

$$R_{CS} = 1 - (1 - R_L)(1 - R_I)(1 - R_{S/C}^{M})$$

where R_L = launch risk
R_I = injection risk
$R_{S/C}$ = spacecraft change of state risk
M = number of spacecraft per launch

In this formulation, the risk is given by:

$$R_{CS} = 0.01\, N_o^{1.3} + (0.01N^{1.3} - 0.01\, N_o^{1.3})^M \quad \text{for} \quad N \geq 2$$

where N_o = the number of changes of state before spacecraft separation (N_o = 2 for the case of Exhibits 36 and 37, i.e., launch + injection)

In the preceding equation the first term represents the risk prior to spacecraft separation and the second term the spacecraft risk. This equation is the basis of the two-spacecraft curve of Exhibit 36 and is analogous to redundant circuits.

The total risk for this major time phase--space flight operations--is given by

$$R_{SFO} = 1 - (1 - R_{MT})(1 - R_{CS})$$

where R_{MT} = risk due to mission time
R_{CS} = risk due to the changes of state

5. Mission Risk Summary

The mission risk combines the mission design, spacecraft subsystem design and development, combined systems testing, and space flight operations risks, and is given by:

$$R_M = 1 - (1 - R_{MD})(1 - R_{SBD})(1 - R_{CST})(1 - R_{SFO})$$

For a program with a single launch, one proceeds through the model and obtains the mission risk by the above relationship. For programs with multiple launches, the program risk is determined by exercising the model iteratively for each launch. Starting with the second launch, some degree of success of the prior launch must be assumed in order to exercise the model. In addition to the degree of success postulated for the determination of the risk on subsequent flights, other items that need to be postulated are (1) diagnostic efficiency in identifying the failures in the prior launch, and (2) time available to develop and incorporate the required changes.

Program risk can therefore vary with the assumptions of the degree of success, diagnostic efficiency, and time available for incorporation of required changes for the preceding flight when calculating the program risk for each flight. The program risk decreases with the number of launches in general, since the experience of previous launches reduces the risk.

III. DEMONSTRATION OF THE RISK MODEL

In order to demonstrate the application of the risk model, two programs have been chosen: Mariner IV for the past program and a large Mars orbiter/lander for the future program.

The results of the Mariner IV risk summary analysis are shown in Exhibits 38 through 42. The results are based on these premises:

1. There was only one nonspacecraft technological innovation utilized--a shroud (adapter)--and there was no backup development planned for the first launch.
2. There were four spacecraft technological innovations:
   a. Canopus sensor--no backup development
   b. Lightweight structure--with backup development
   c. Communications--with backup development
   d. Data management--with backup development
3. The scenario for the failure-diagnosis-development fix effort is as follows:
   a. The shroud failed on the first launch
   b. The difficulty was promptly and properly diagnosed
   c. The development fix was made in time for the second launch

An inspection of Exhibit 42 shows that the risk for the Mariner IV program is reduced substantially for the second launch primarily because of the removal of the nonspacecraft and spacecraft technological innovation risks.

The description for the future mission example was taken from Reference 18, and the results for this Mars orbiter/lander mission are shown in Exhibits 43 through 47. The premises for these calculations are as follows:

4. There were no nonspacecraft technological innovations.
5. There were four spacecraft technological innovations:
   a. Propulsion module structure and propellant pressurization--with backup development

b. Entry capsule descent system--no backup development (namely, the stabilization problem of a low m/C_DA capsule suspended beneath a parachute in possible high winds)

c. Sterilizable batteries for the entry capsule--no backup development

d. Descent rocket propulsion with high (9 : 1) throttling ratio--no backup development

6. The scenario for the failure-diagnosis-development fix effort is as follows:

a. On the first dual spacecraft launch, one spacecraft fails to retrofire and continues in a fly-by mode; the second of the spacecraft pair successfully enters Martian orbit and ejects a capsule which crashes on or slightly before landing, resulting in no surface measurements being made.

b. The difficulties in all failure modes were promptly and properly diagnosed.

c. The development fixes were made in time for the second launch.

An inspection of Exhibit 47 shows the substantial contribution of combined system testing risk to mission risk for both launches.

IV. SCOPE AND ACCURACY OF THE RISK MODEL

In a small analytical study such as this, much of the work is of an exploratory nature and great accuracy is difficult to achieve. The sections of the model based on mature subsystem technologies are felt to be quite accurate, possibly ±10 percent; however, those sections which rely heavily on engineering judgment could result in errors of 25 to 50 percent.

In addition, the model was calibrated using the Mariner IV program of two launches. The model was then adjusted slightly and tested for relative risk in the various phases. These minor adjustments were made on the basis of engineering judgment and resulted in a program risk, $R_p = 0.52$, for the second launch. The model was then deliberately and uniformly adjusted in all phases and categories to provide $R_p = 0.50$ for the Mariner IV second launch as a baseline for future estimates.

In estimating the risk of the future program, a Mars orbiter/lander, no calibration was possible; however, this exercise did result in reevaluating and increasing the risk due to sterilization and combined systems testing. This appears valid since the Mariner IV, a single module spacecraft, was not sterilized and the risk estimating relationship for sterilization was not calibrated in the demonstration of the model on this past program.

V. SUMMARY AND CONCLUSIONS

In summary, this small exploratory study to develop a risk model for unmanned space exploration missions has been built around a framework of the time phases of a large program utilizing the system management mode of implementation.

The following conclusions were reached as a result of the study:

1. Probably less effort should have been spent on subsection II. D. 2, Spacecraft Subsystem Design and Development; however, the types of risk estimating relationships shown would have forewarned of program failures such as Dyna-Soar and Skybolt.

2. a. Under the mission design phase, probably the most important category is schedule risk, since the program manager will tend to minimize nonspacecraft technological risks and use a simple operational mode.

   b. Under the mature technology categories in Phase D, the risk for spacecraft subsystem design and development is usually low or nonexistent; however, the risk relationships shown for spacecraft technological innovations encourage the program manager to reduce the number of innovations or to carry alternate developments or options.

   c. The program manager probably faces the greatest risks in the combined systems testing phase: that he is testing to the wrong environment or cannot simulate the environment for technical, schedule, or financial reasons; that he is degrading the performance of the spacecraft by using an extreme sterilization intensity; or that he will learn later in the flight operations phase that subsystem and module interaction failures were not uncovered within his selected level of testing.

   d. The space flight operations phase shows the influence of mission time and changes of state on risk; although there may be some overlap in changes of state risk and operational mode complexity risk, time and resources did not allow the opportunity to examine this situation for potential minor recalibration.

3. Special care has been taken to develop this risk model so that it may be used as a matched set with the cost model shown in Reference 2 to provide trades of schedule, risk, and cost at the program level for various system design candidates.

4. The model does not assess risk in an absolute sense but in a relative sense, using Mariner IV as a baseline case.

5. The model has the mildly coercive effect of forcing any program manager using the model to think about the interrelationships and interactions in managing a large space exploration program.

6. Attention is invited to the intriguing possibility that the model, by virtue of its form and content, could be extended to provide a spacecraft management development and training game for program managers.

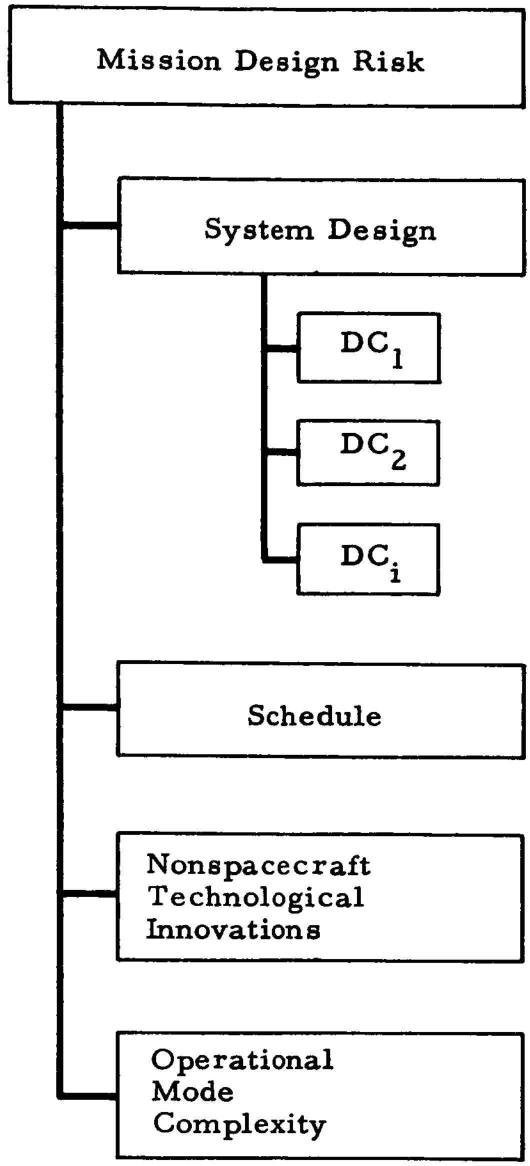


EXHIBIT 1 - MISSION DESIGN RISK

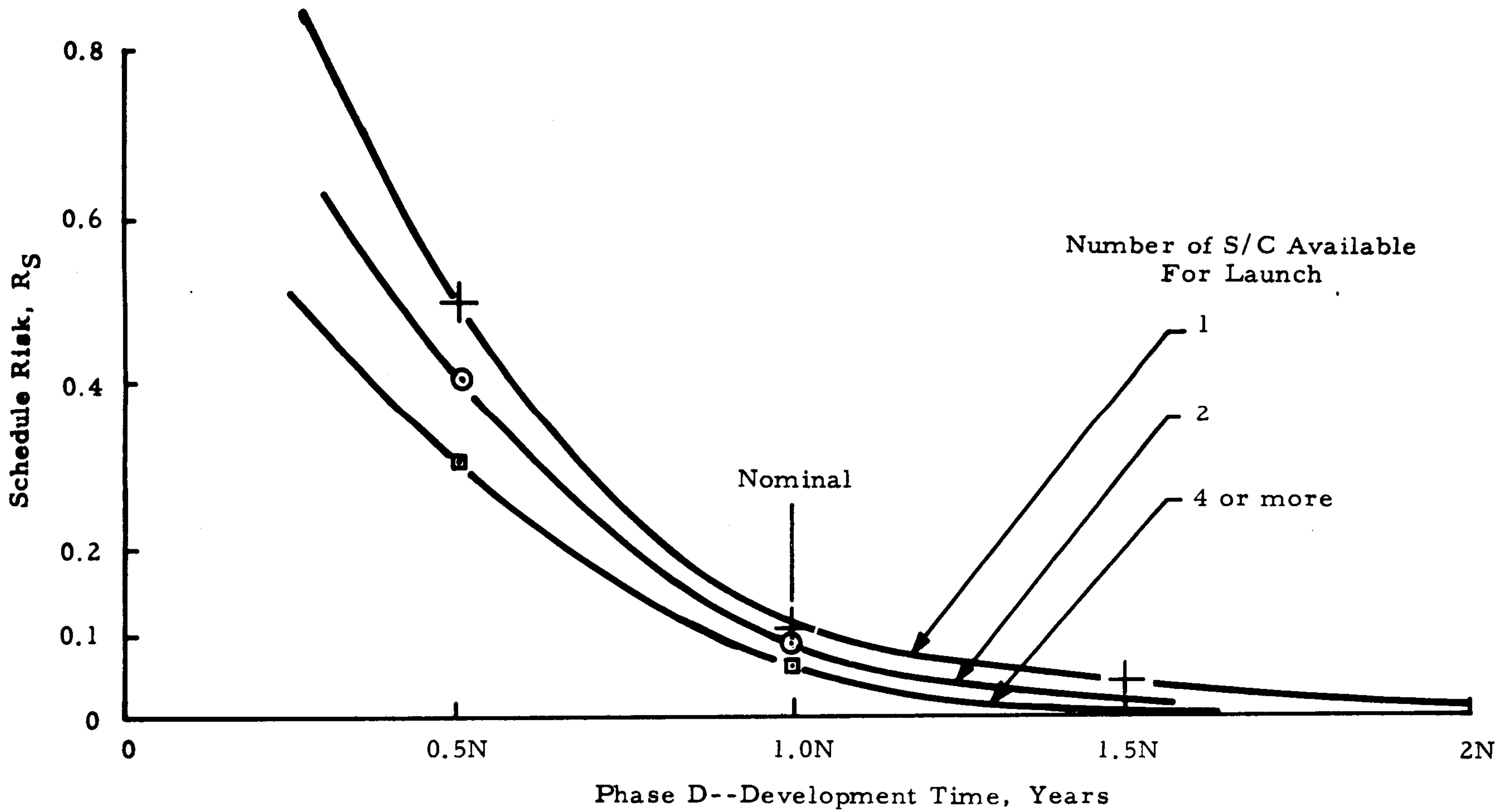


EXHIBIT 2 - SCHEDULE RISK, R_S

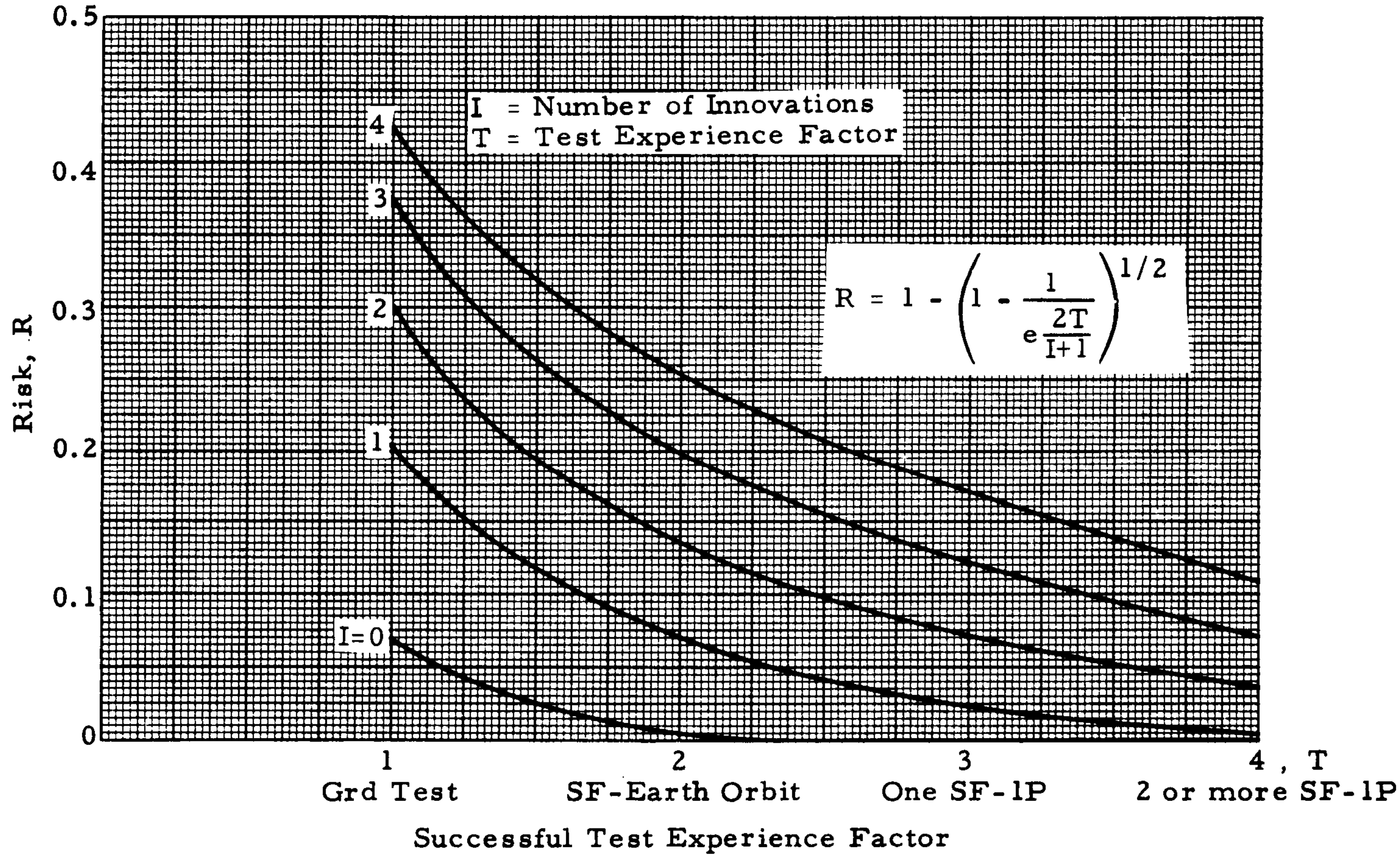


EXHIBIT 3 - NONSPACECRAFT TECHNOLOGICAL INNOVATION RISK--NO BACKUP DEVELOPMENT

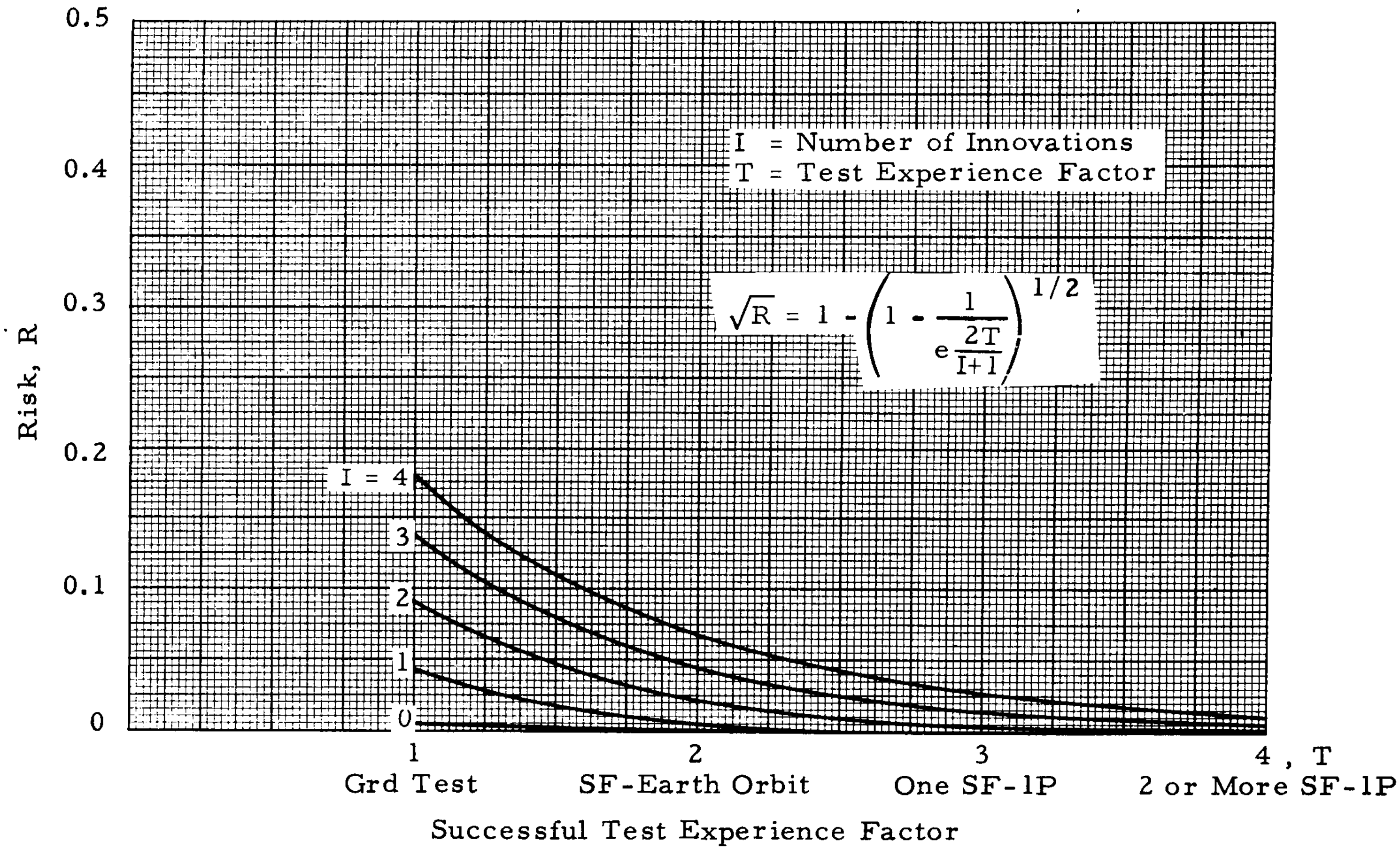


EXHIBIT 4 - NONSPACECRAFT TECHNOLOGICAL INNOVATION RISK--ONE BACKUP DEVELOPMENT PER INNOVATION

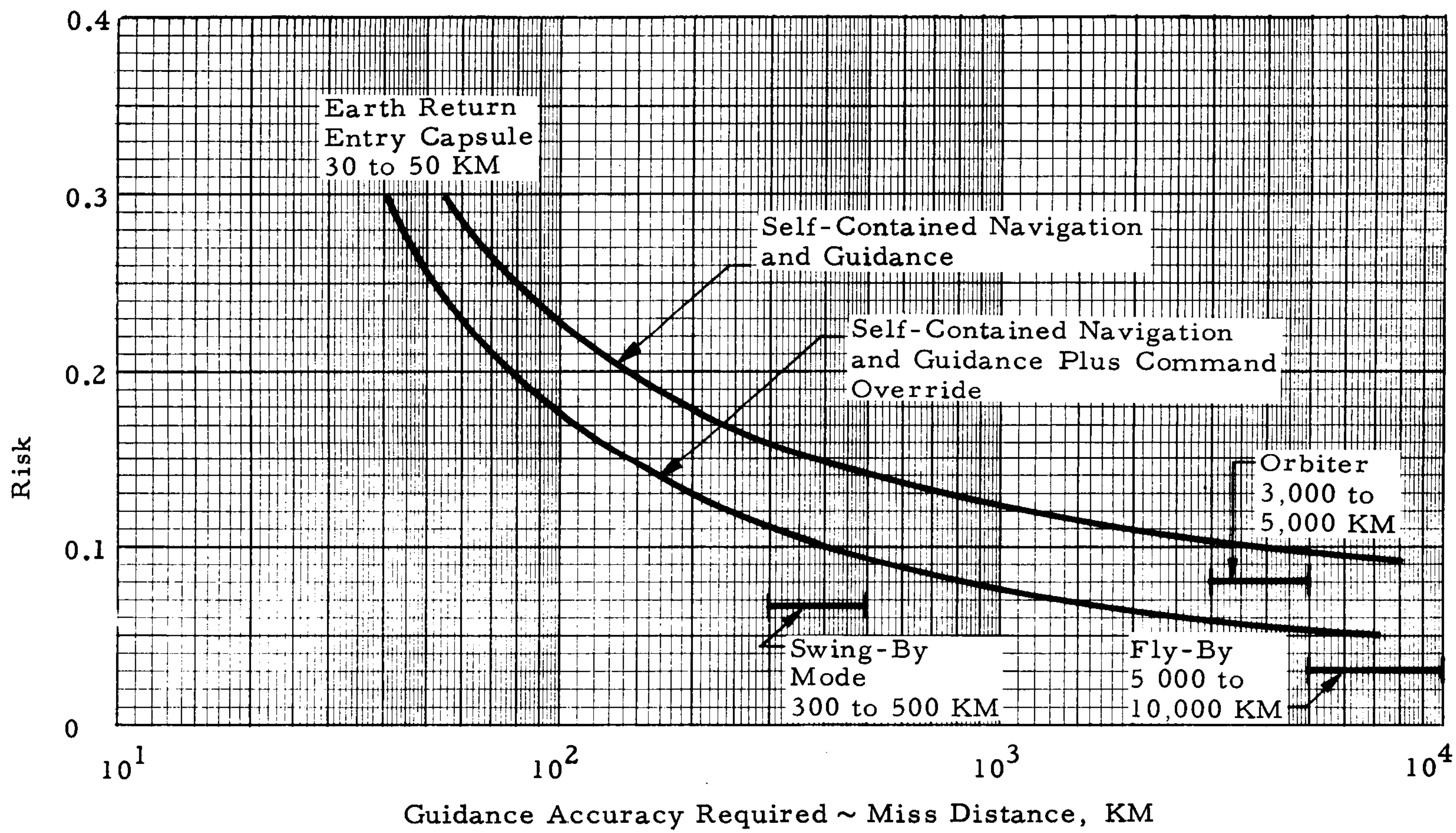


EXHIBIT 5 - OPERATIONAL MODE COMPLEXITY

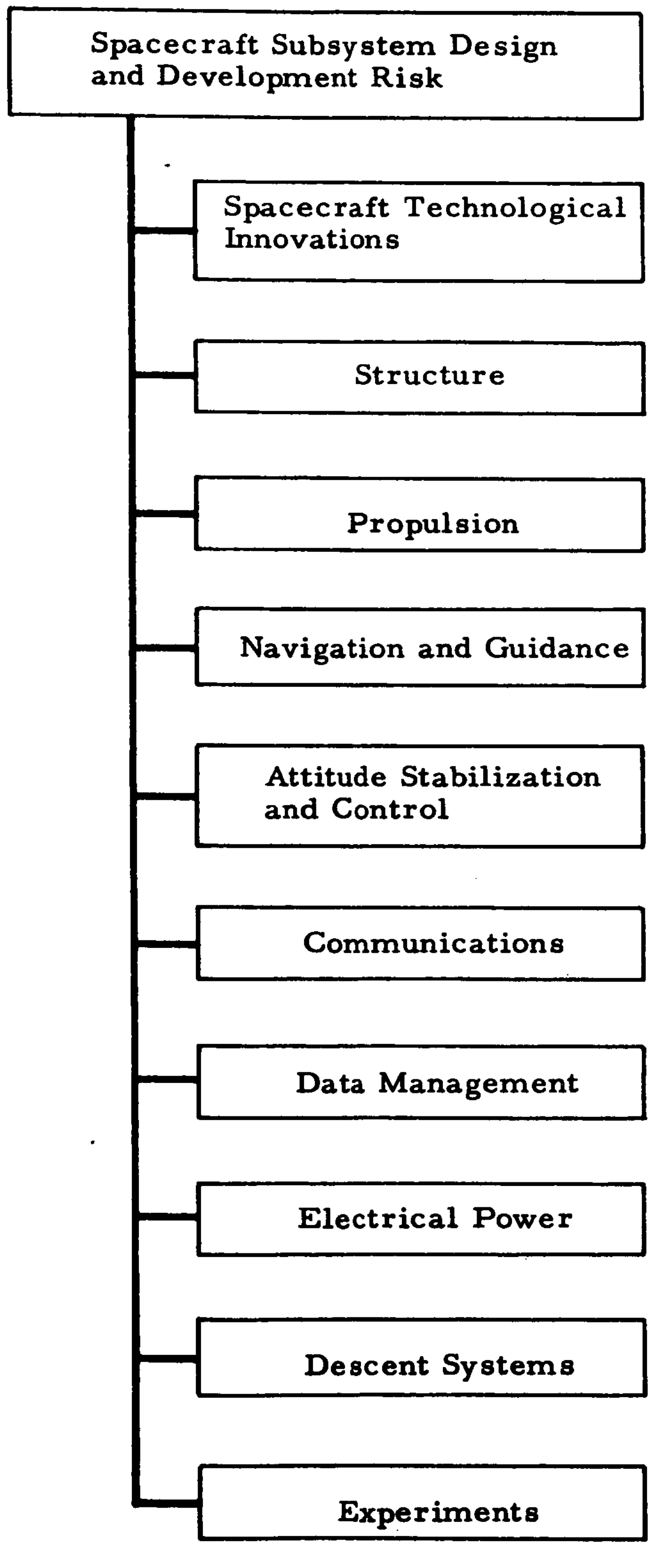


EXHIBIT 6 - SPACECRAFT SUBSYSTEM DESIGN AND DEVELOPMENT RISK

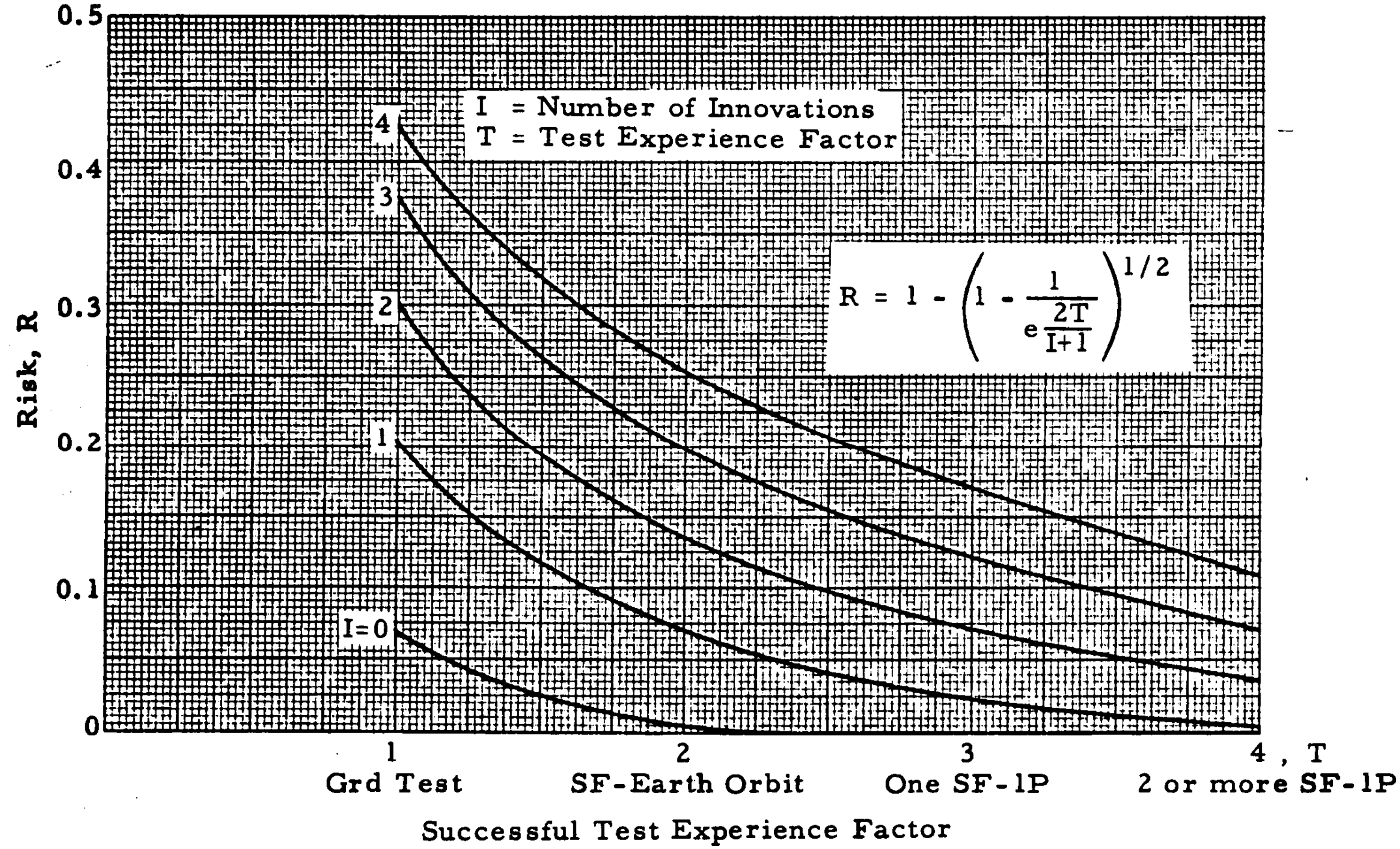


EXHIBIT 7 - SPACECRAFT TECHNOLOGICAL INNOVATION RISK--NO BACKUP DEVELOPMENT

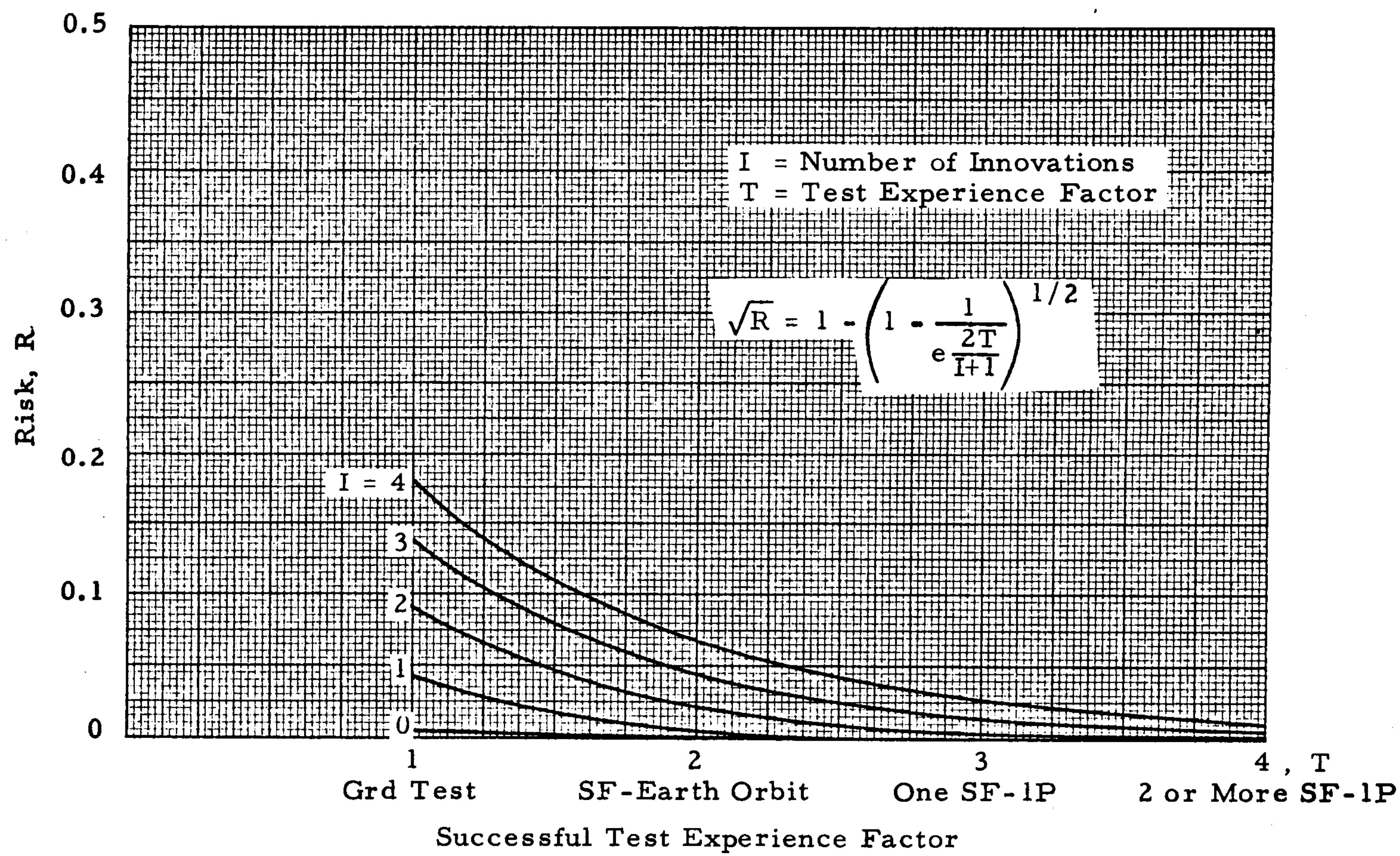


EXHIBIT 8 - SPACECRAFT TECHNOLOGICAL INNOVATION RISK--ONE BACKUP DEVELOPMENT PER INNOVATION

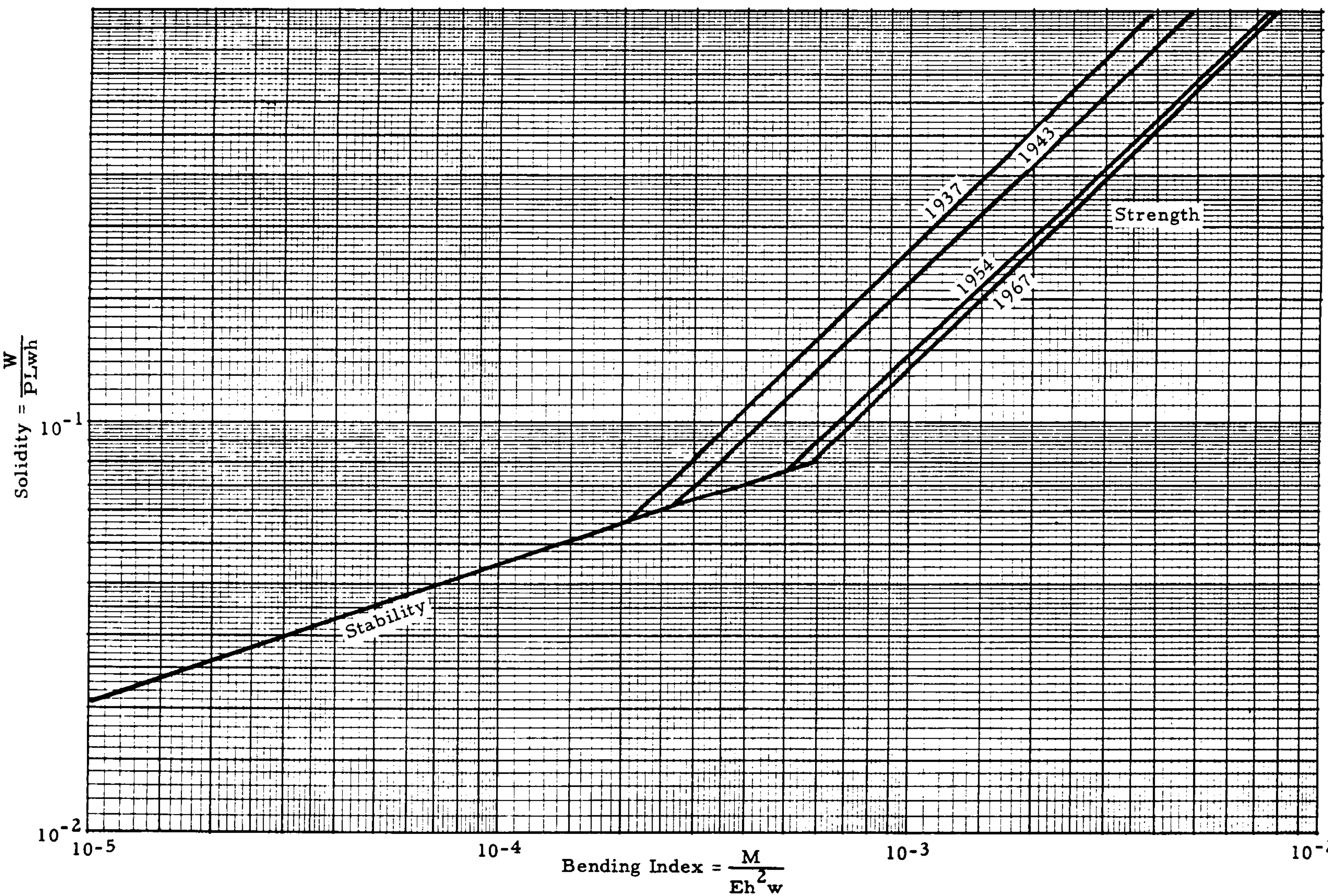


EXHIBIT 9 - MULTIWEB BOX BEAM ALUMINUM

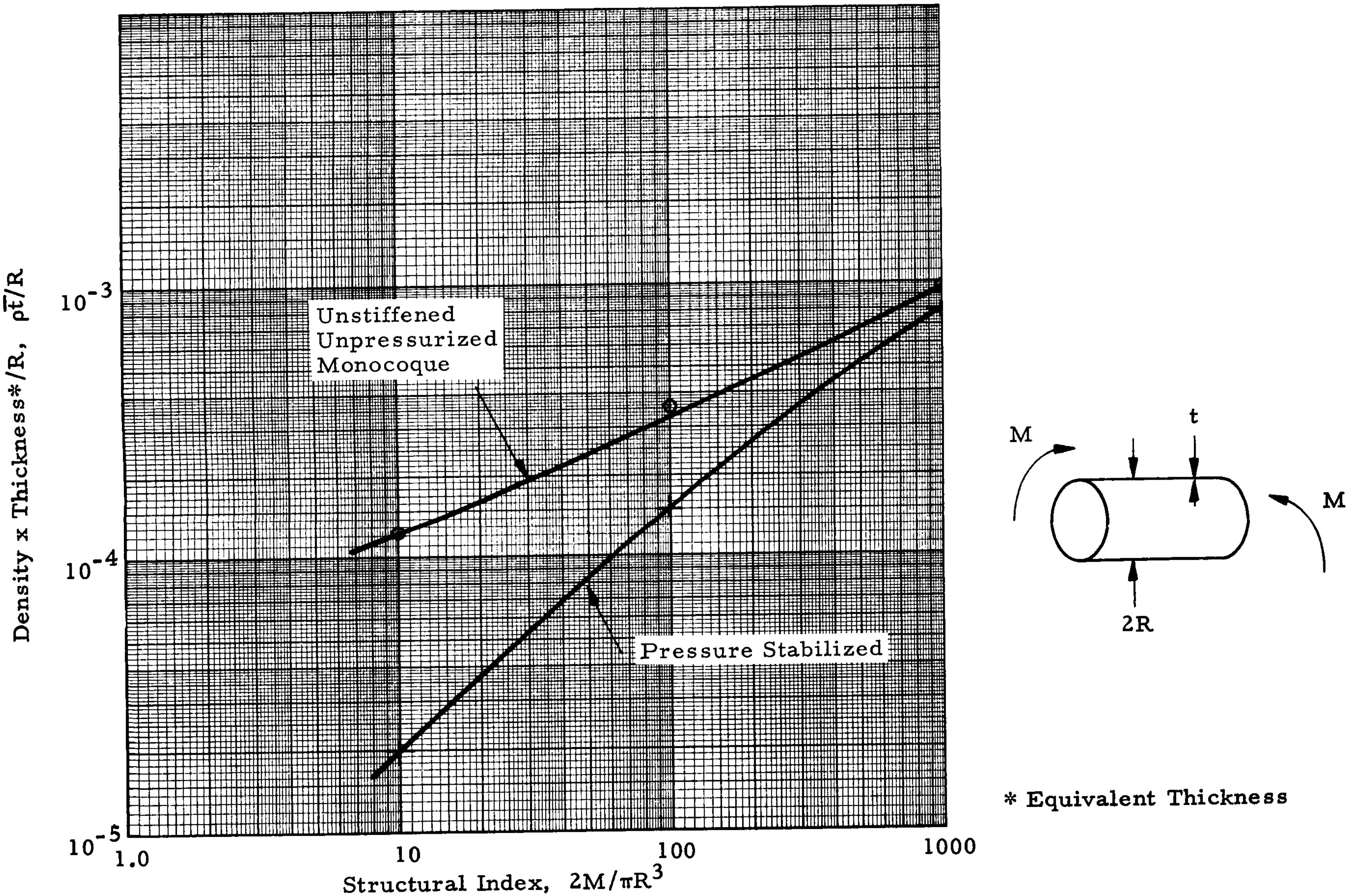
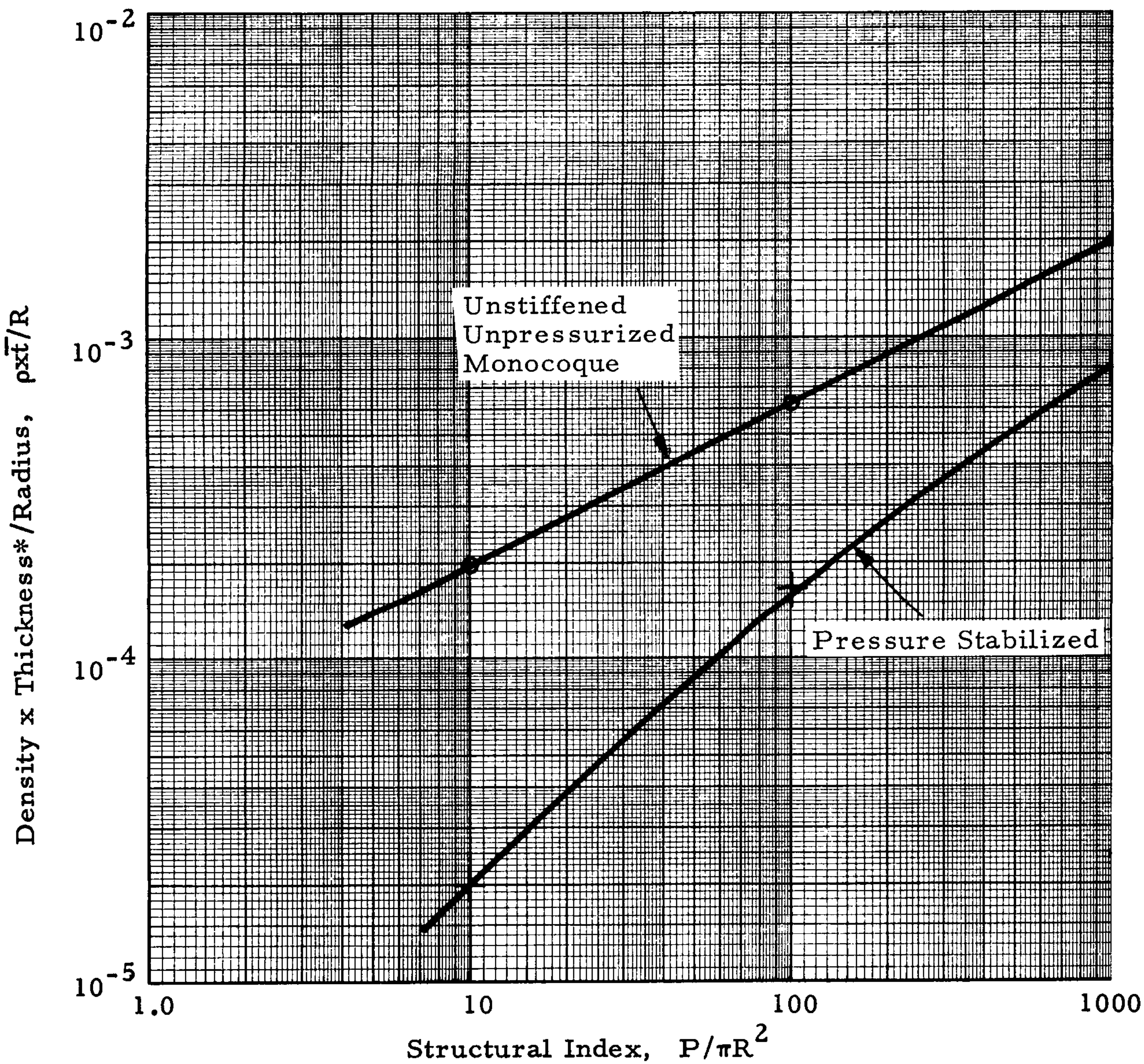
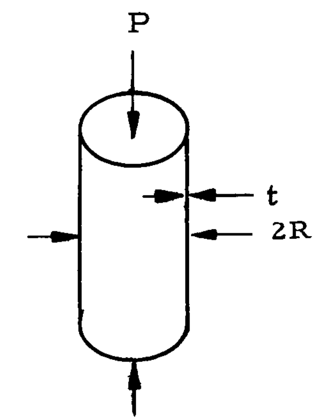


EXHIBIT 10 - CYLINDRICAL SHELLS IN BENDING





* Equivalent Thickness

EXHIBIT 11 - CYLINDRICAL SHELLS IN COMPRESSION

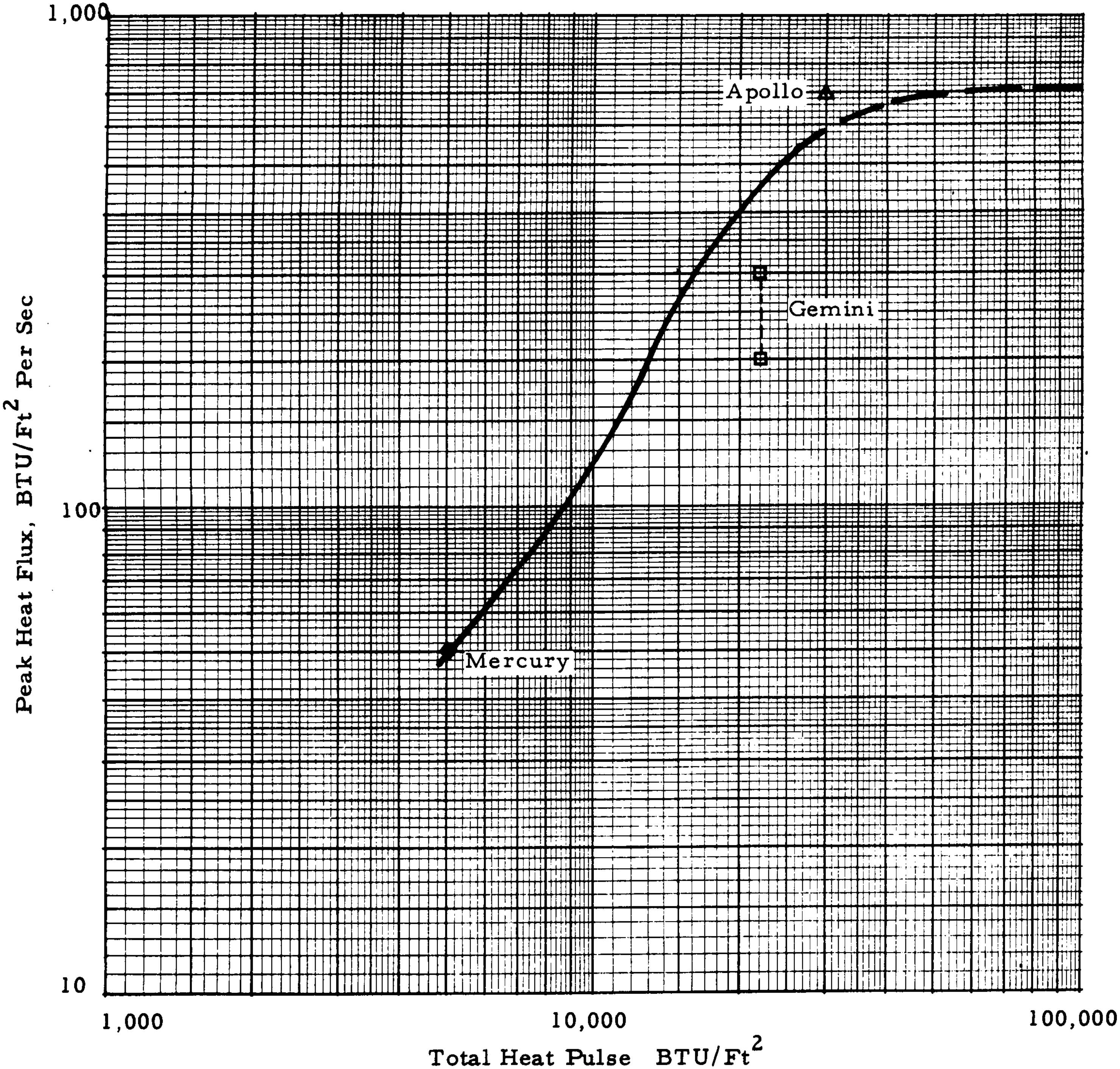


EXHIBIT 12 - THERMAL PROTECTION SYSTEM--BALLISTIC ENTRY SPACECRAFT (HEAT FLUX VERSUS TOTAL HEAT PULSE)

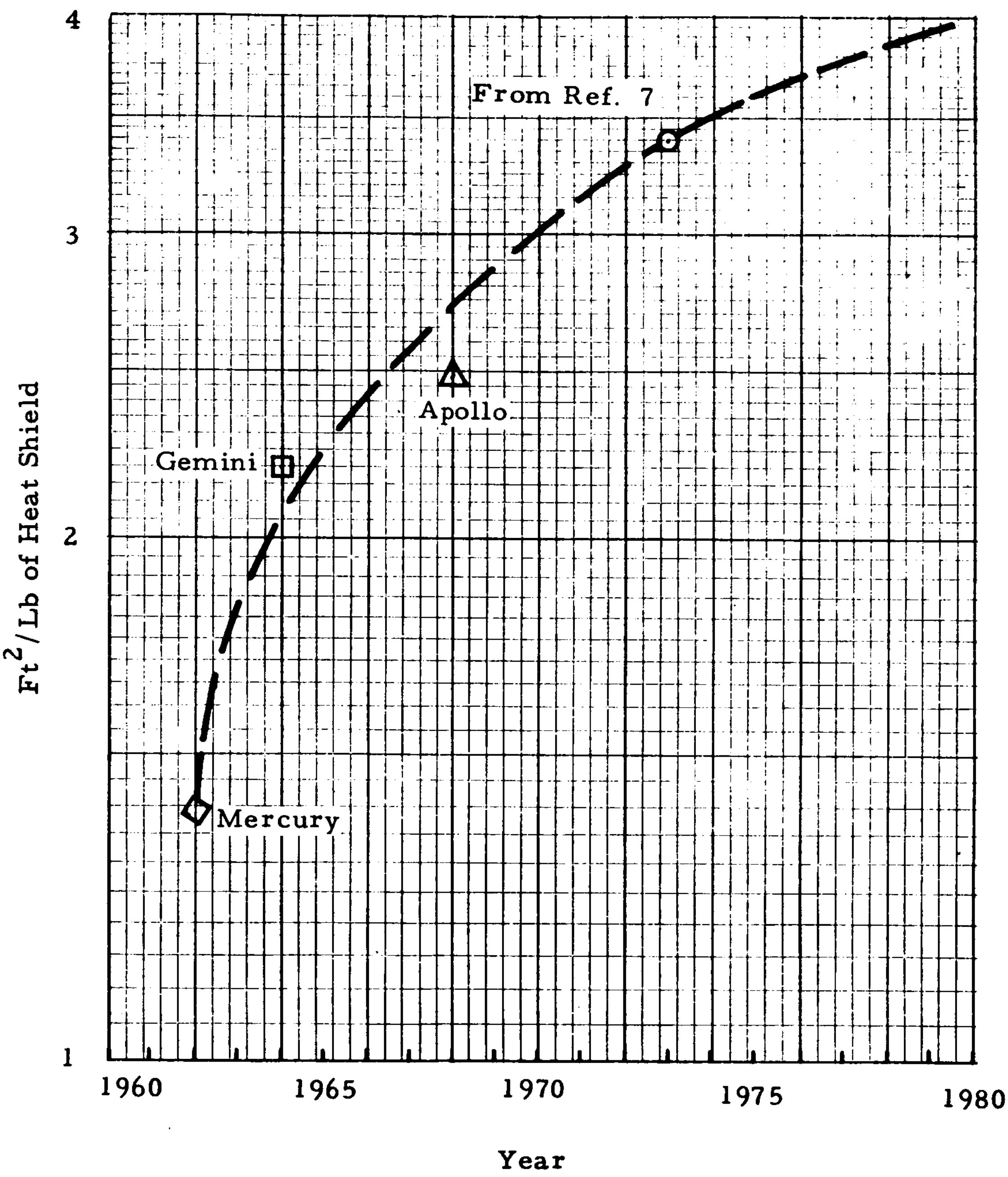


EXHIBIT 13 - THERMAL PROTECTION SYSTEM--BALLISTIC ENTRY SPACECRAFT (HEAT SHIELD)

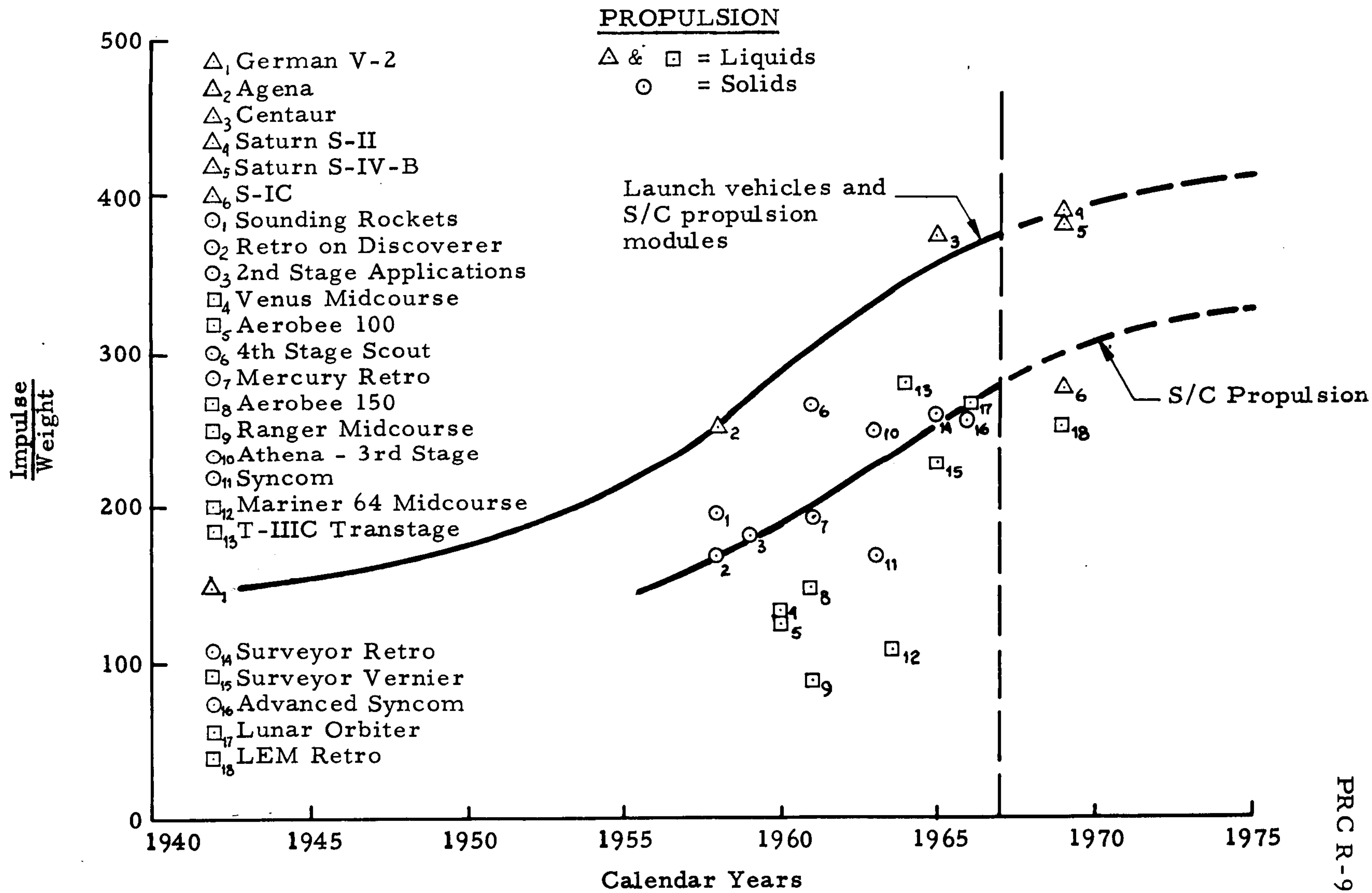


EXHIBIT 14 - PROPULSION

EXHIBIT 15 - PROPULSION RISK

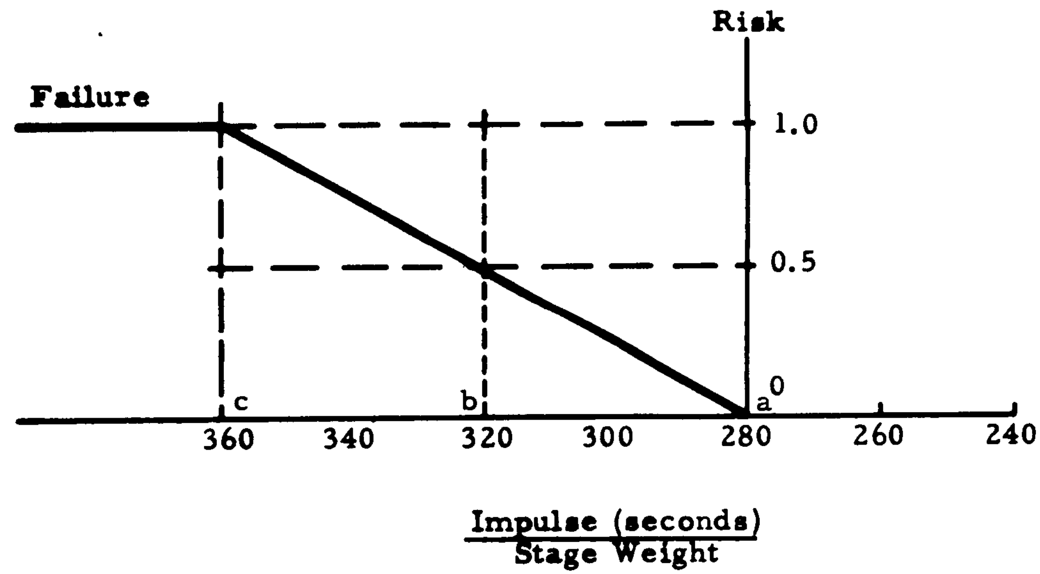


EXHIBIT 16 - PROPULSION SUBSYSTEM DESIGN AND DEVELOPMENT RISK

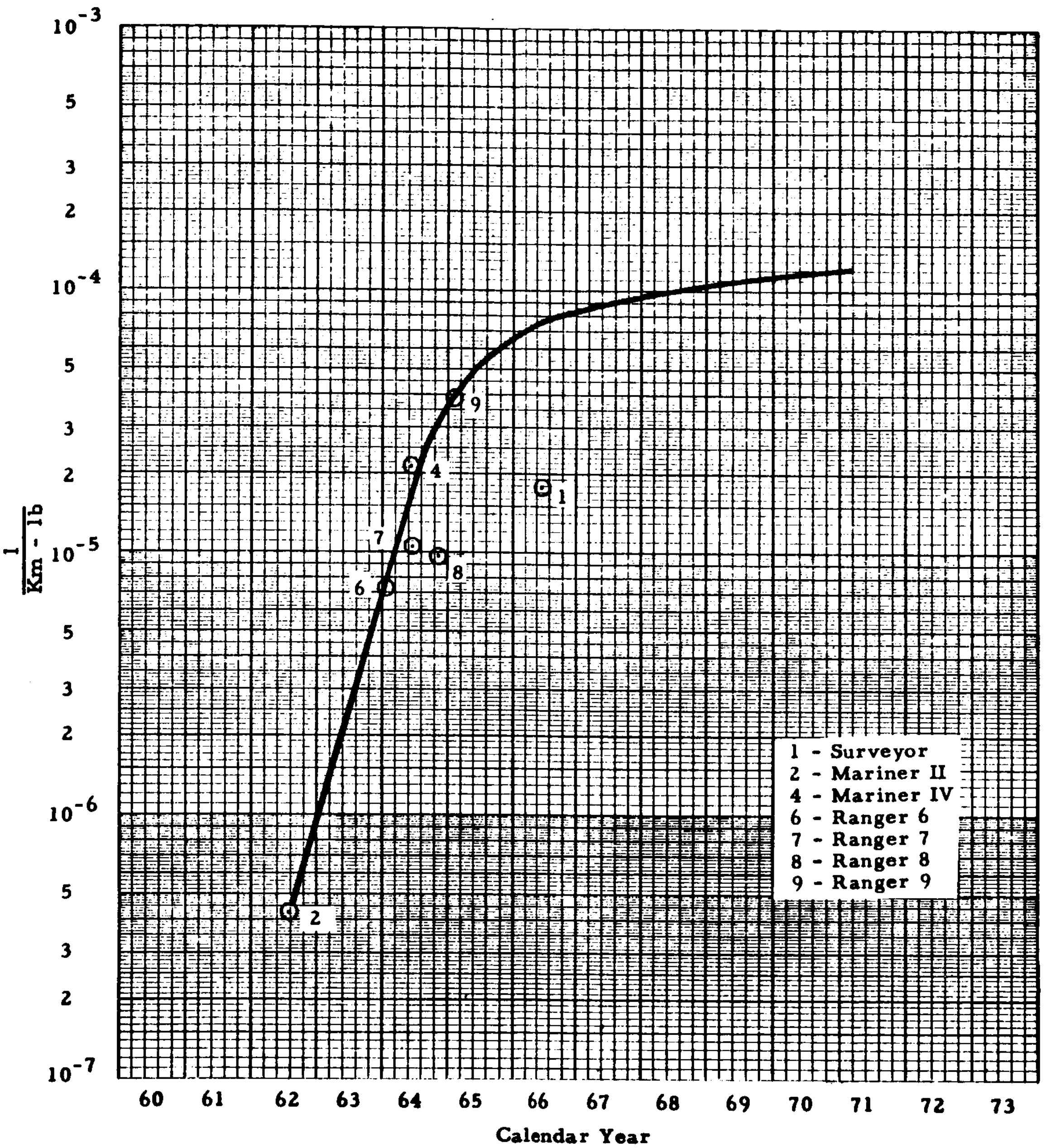


EXHIBIT 17 - NAVIGATION AND GUIDANCE

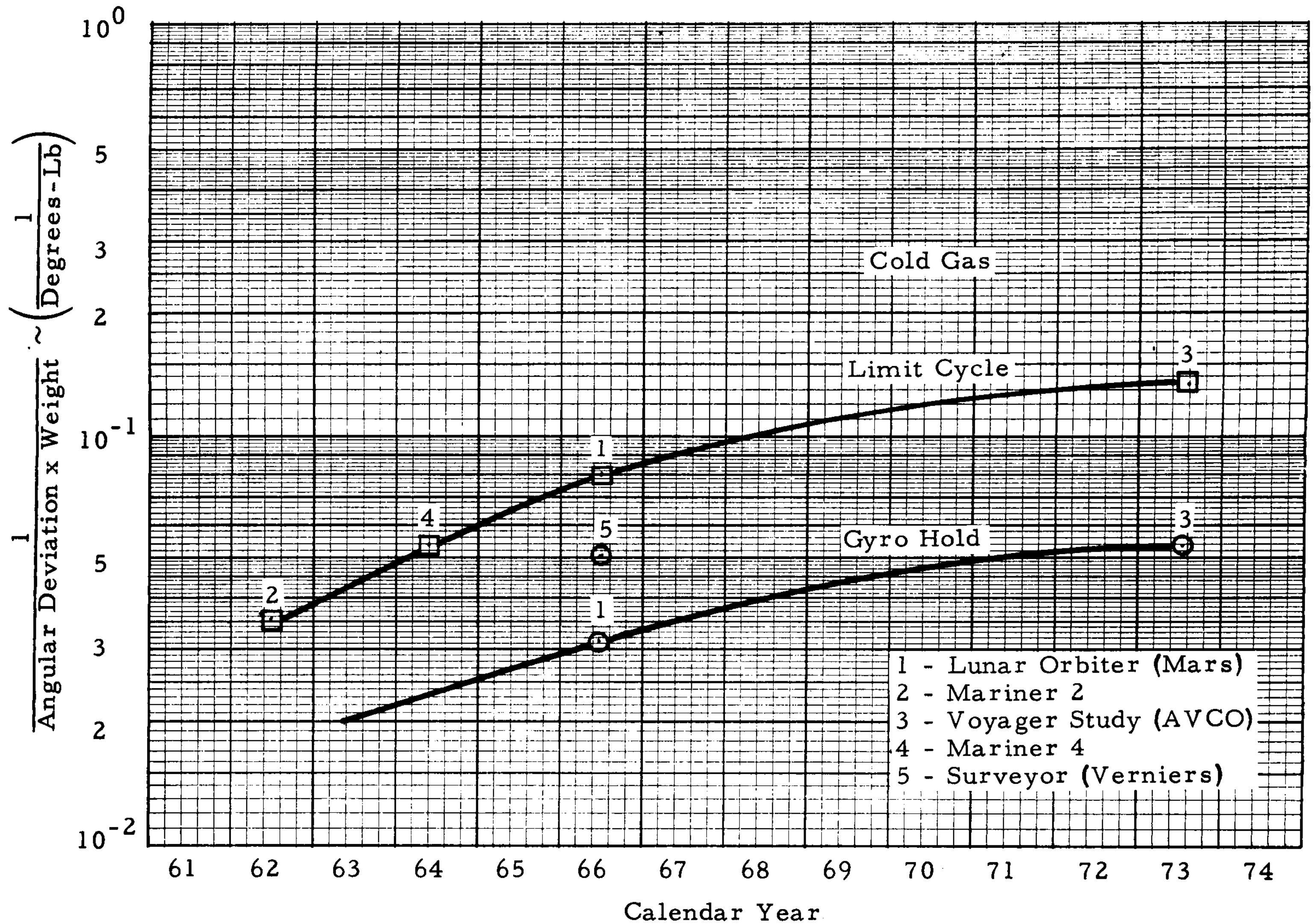


EXHIBIT 18 - ATTITUDE STABILIZATION

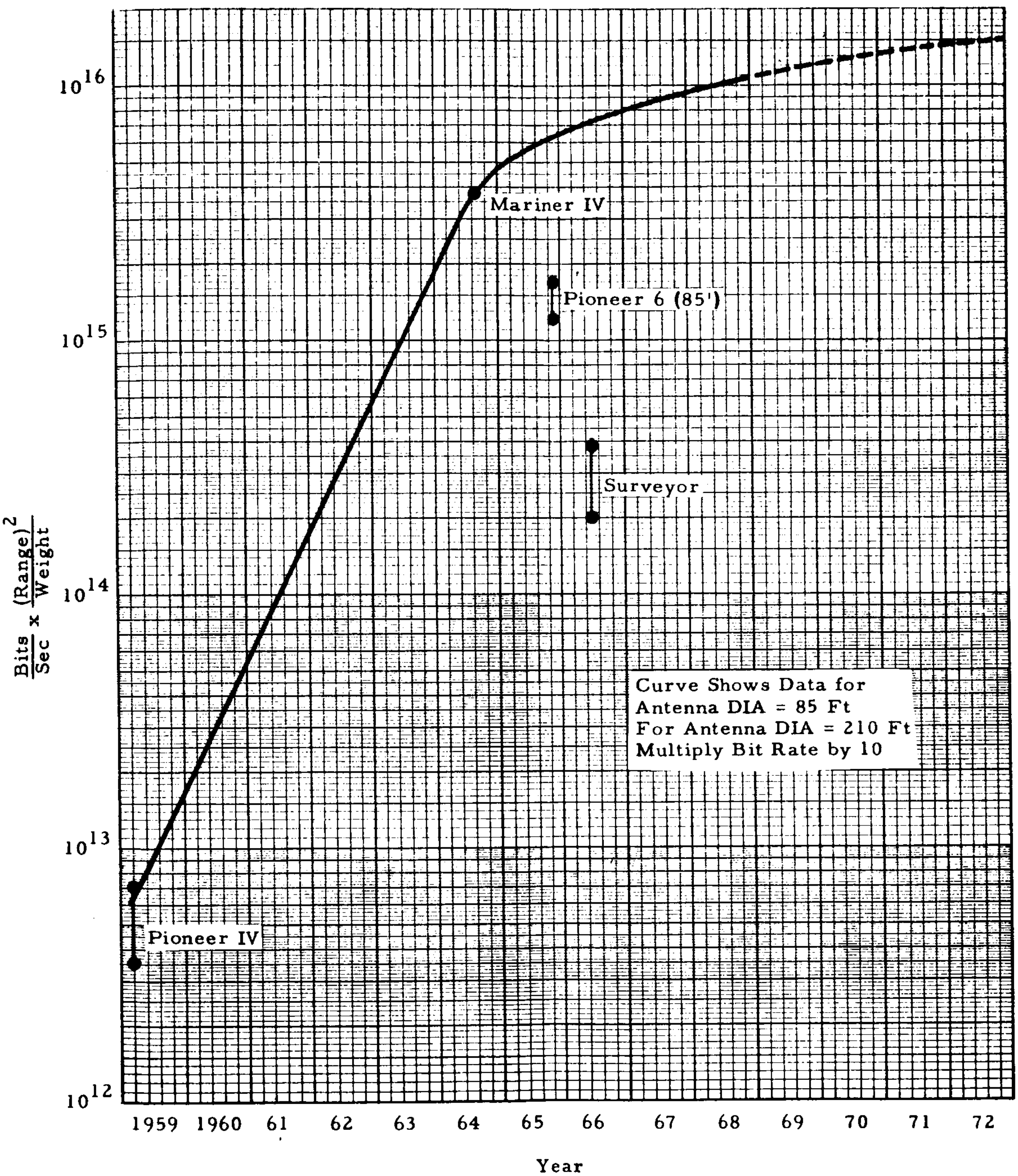


EXHIBIT 19 - SPACE COMMUNICATIONS

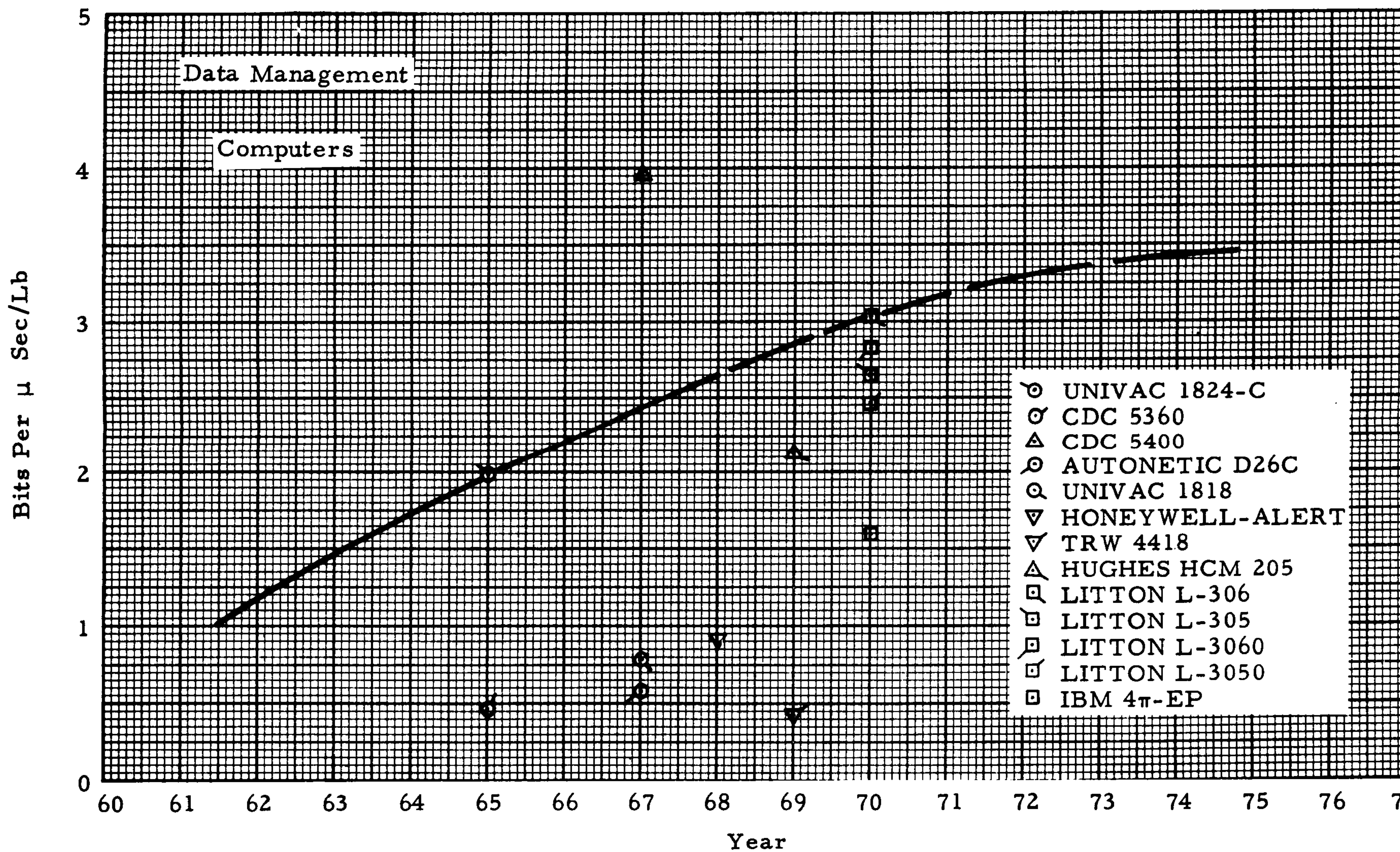


EXHIBIT 20 - DATA MANAGEMENT COMPUTERS--WEIGHT

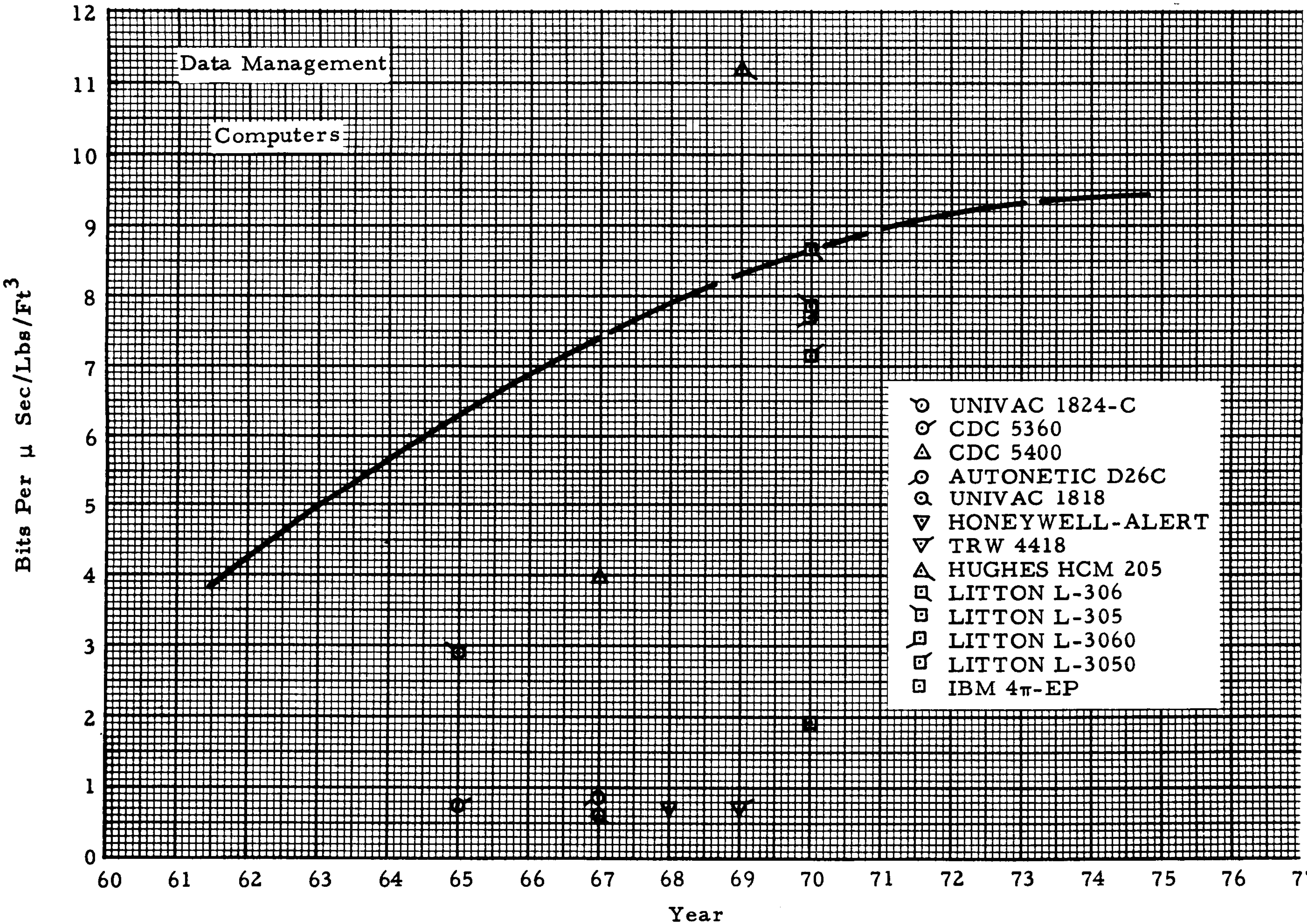


EXHIBIT 21 - DATA MANAGEMENT COMPUTERS--VOLUME

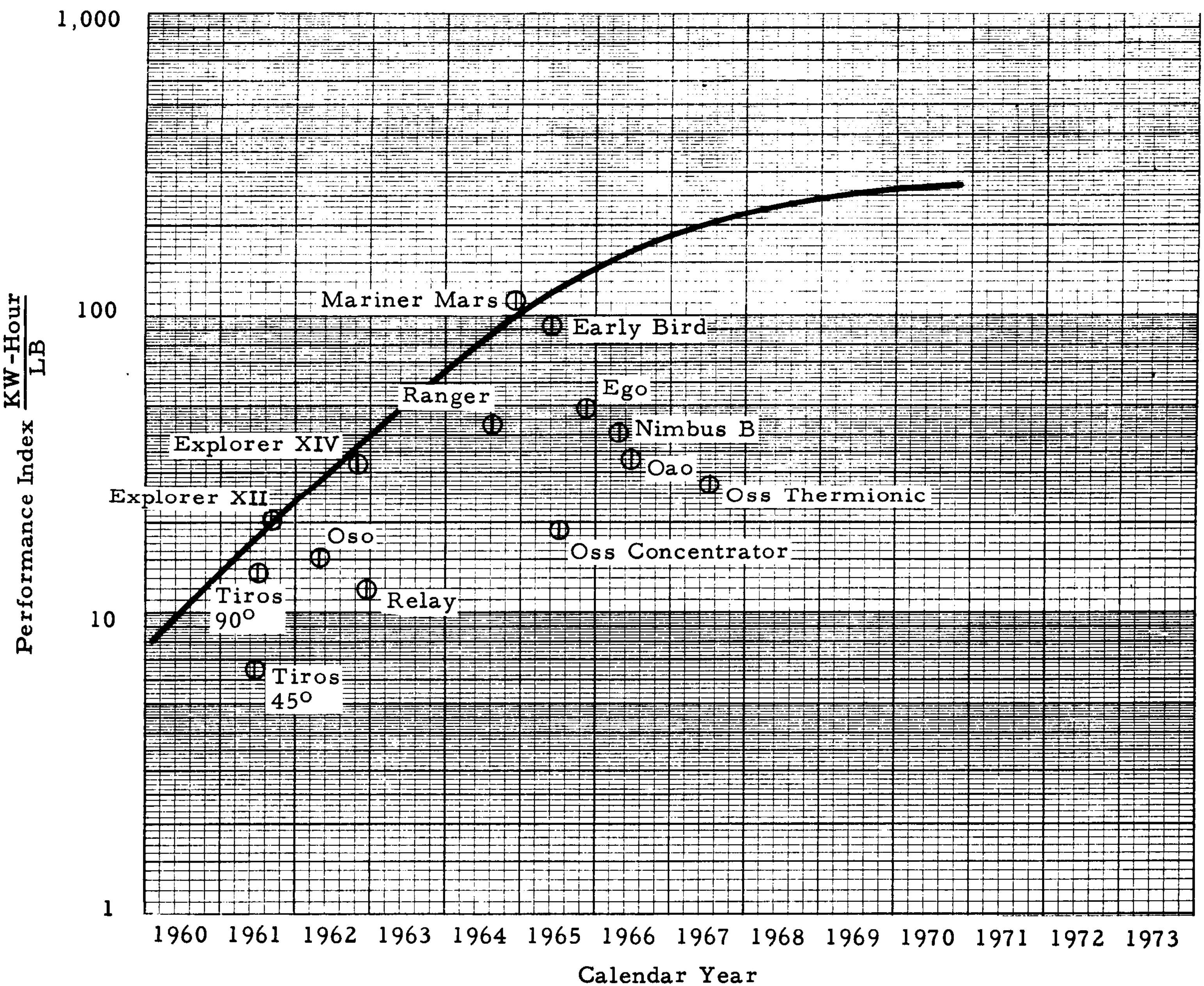


EXHIBIT 22 - ELECTRICAL POWER--SOLAR CELLS

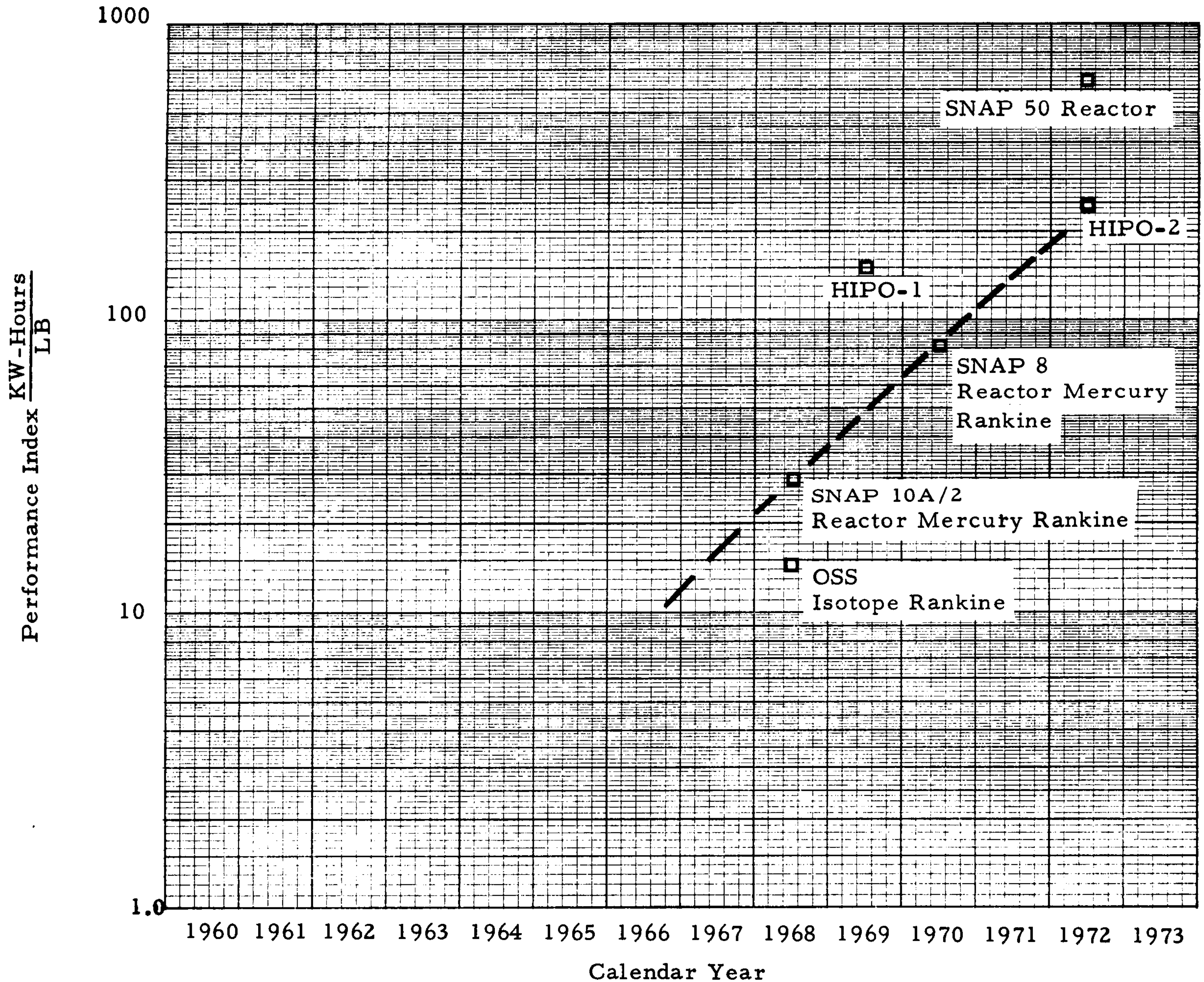


EXHIBIT 23 - ELECTRICAL POWER--NUCLEAR DYNAMIC

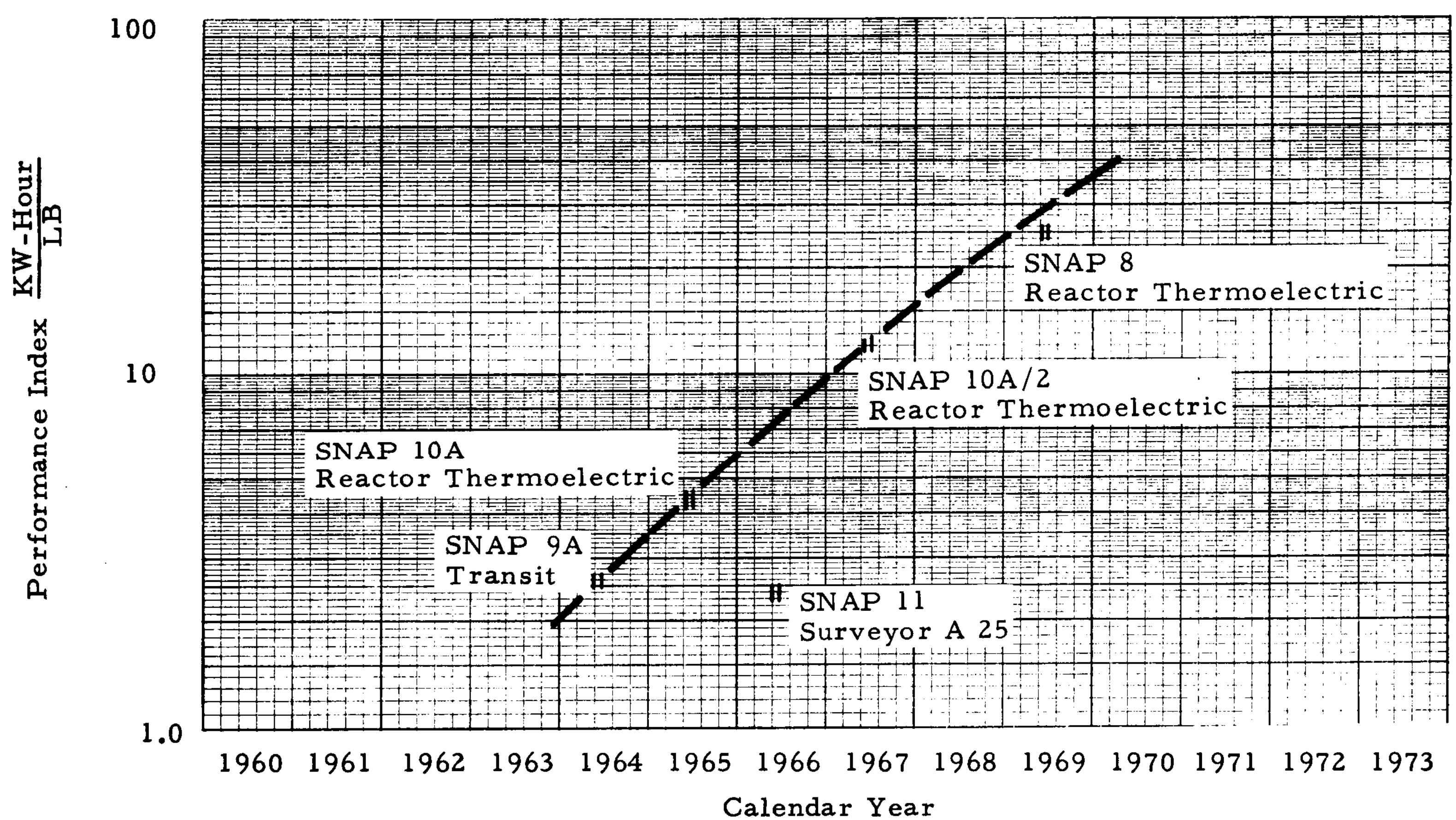


EXHIBIT 24 - ELECTRICAL POWER--NUCLEAR THERMOELECTRIC

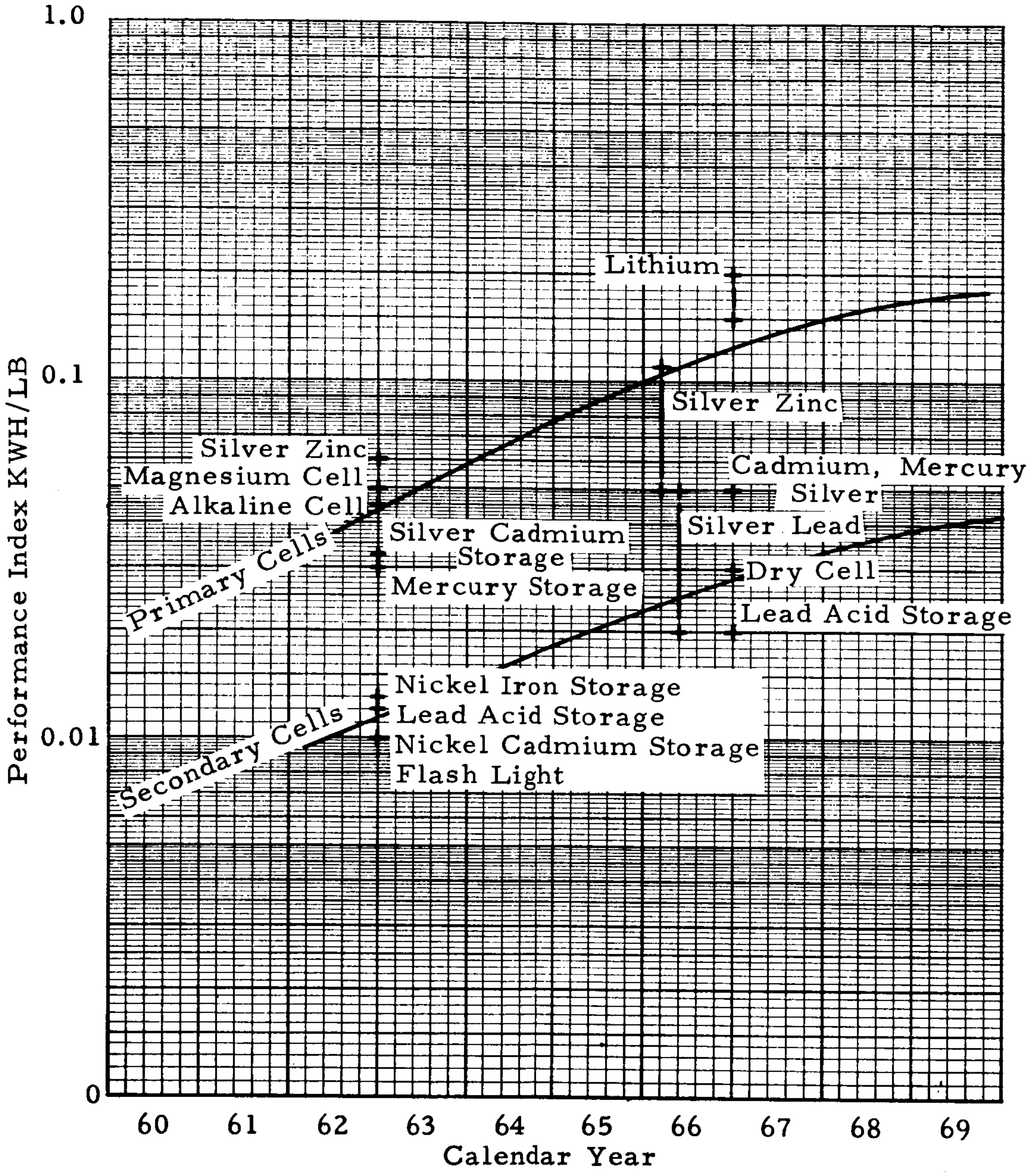


EXHIBIT 25 - SPACE POWER SYSTEMS BATTERIES

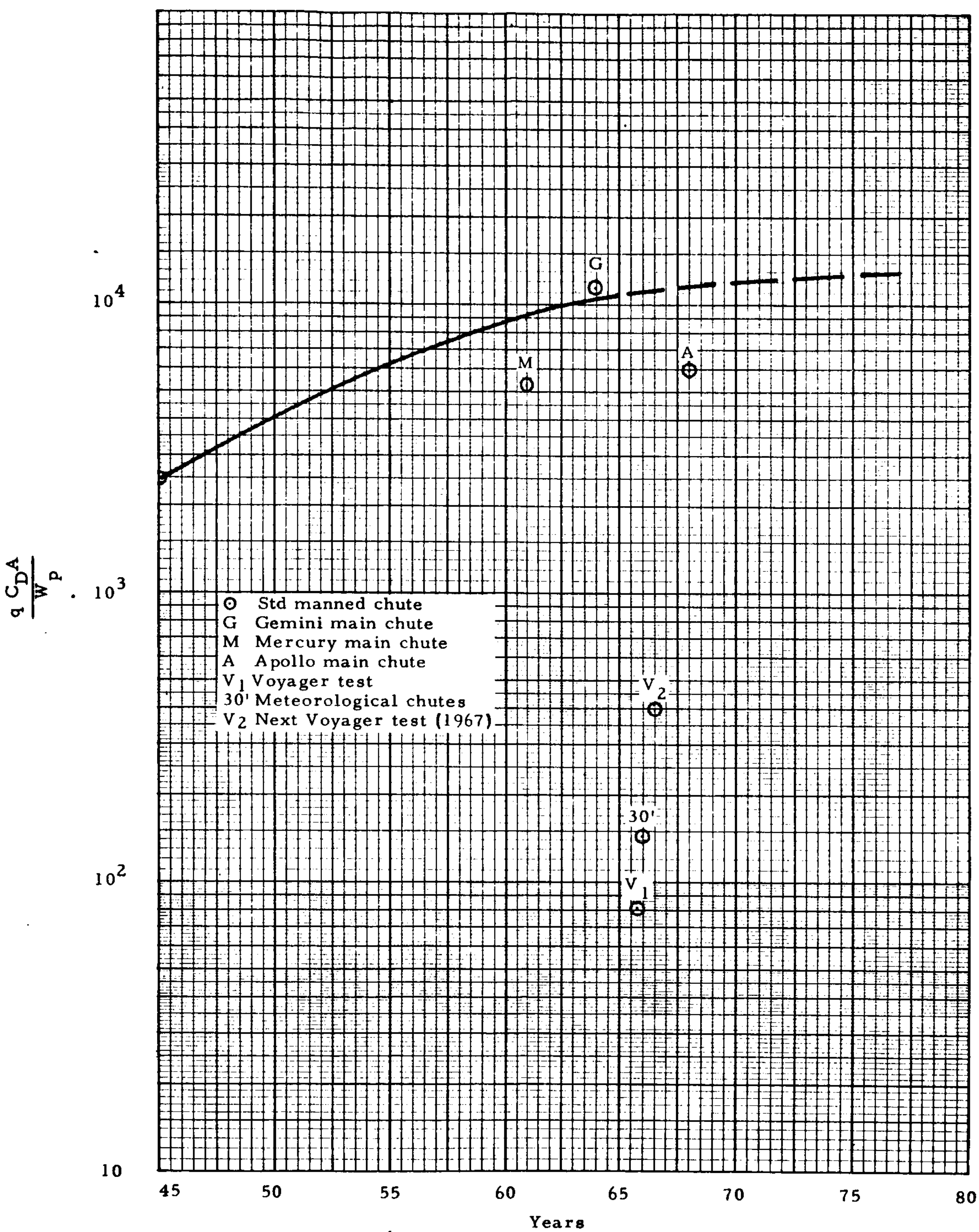


EXHIBIT 26 - DESCENT SYSTEMS

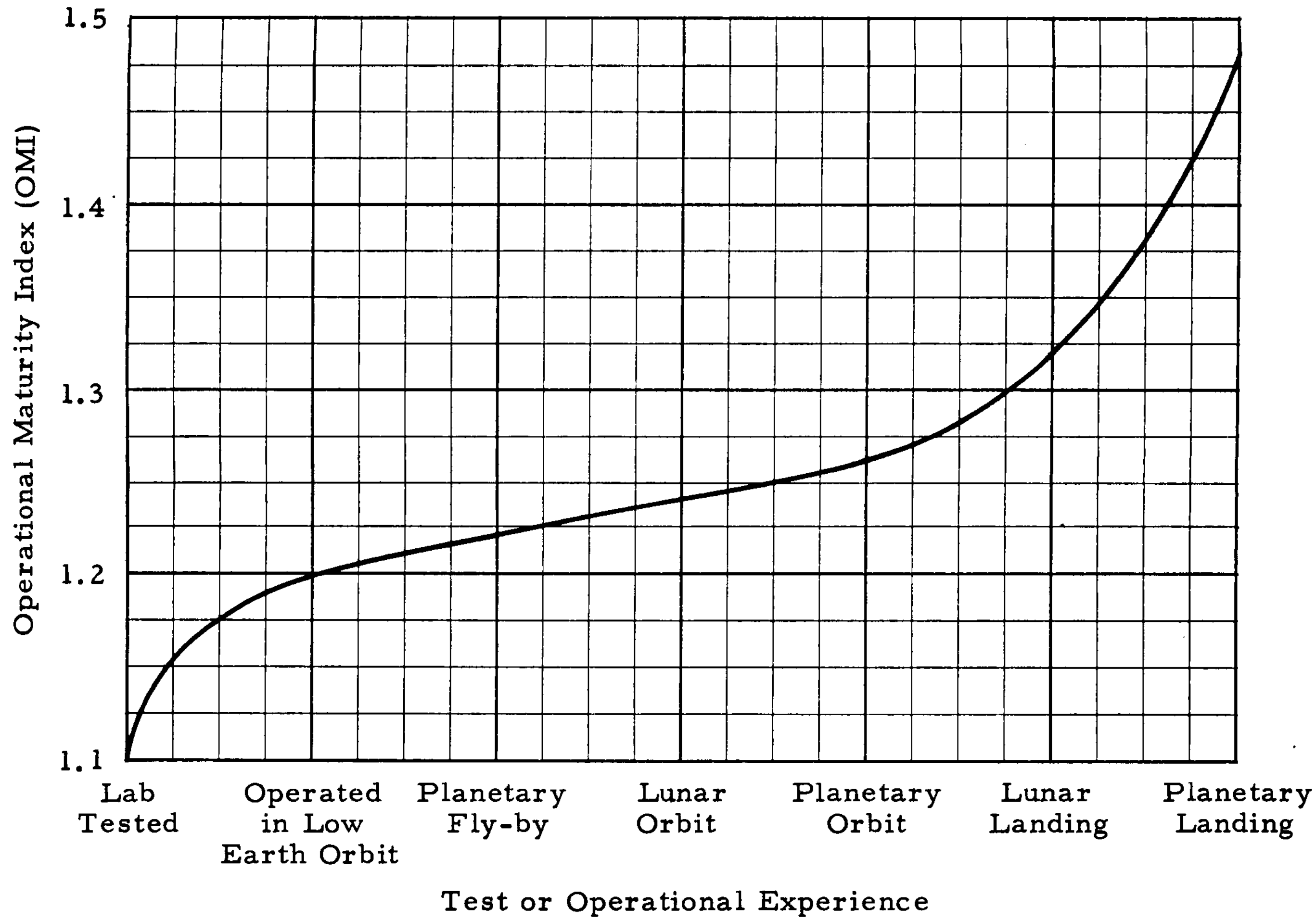


EXHIBIT 27 - EXPERIMENTS OPERATIONAL MATURITY INDEX

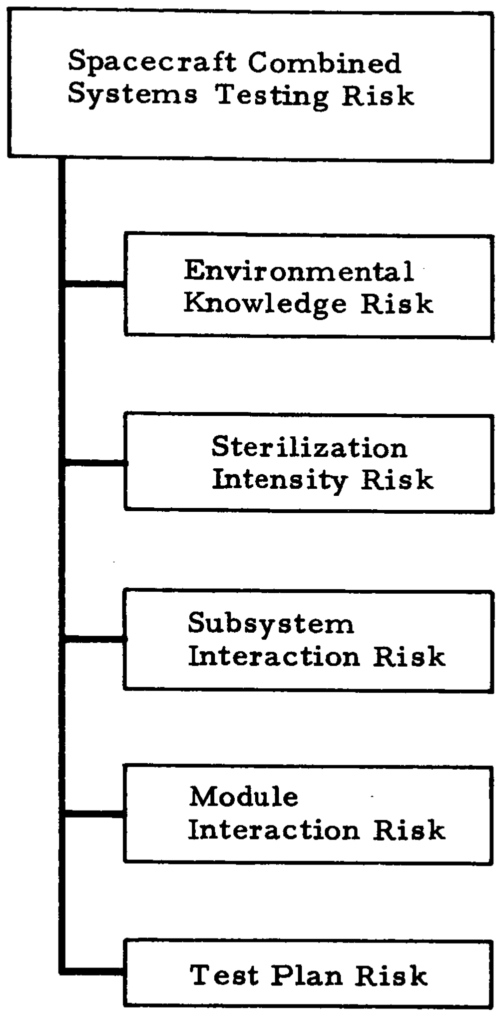
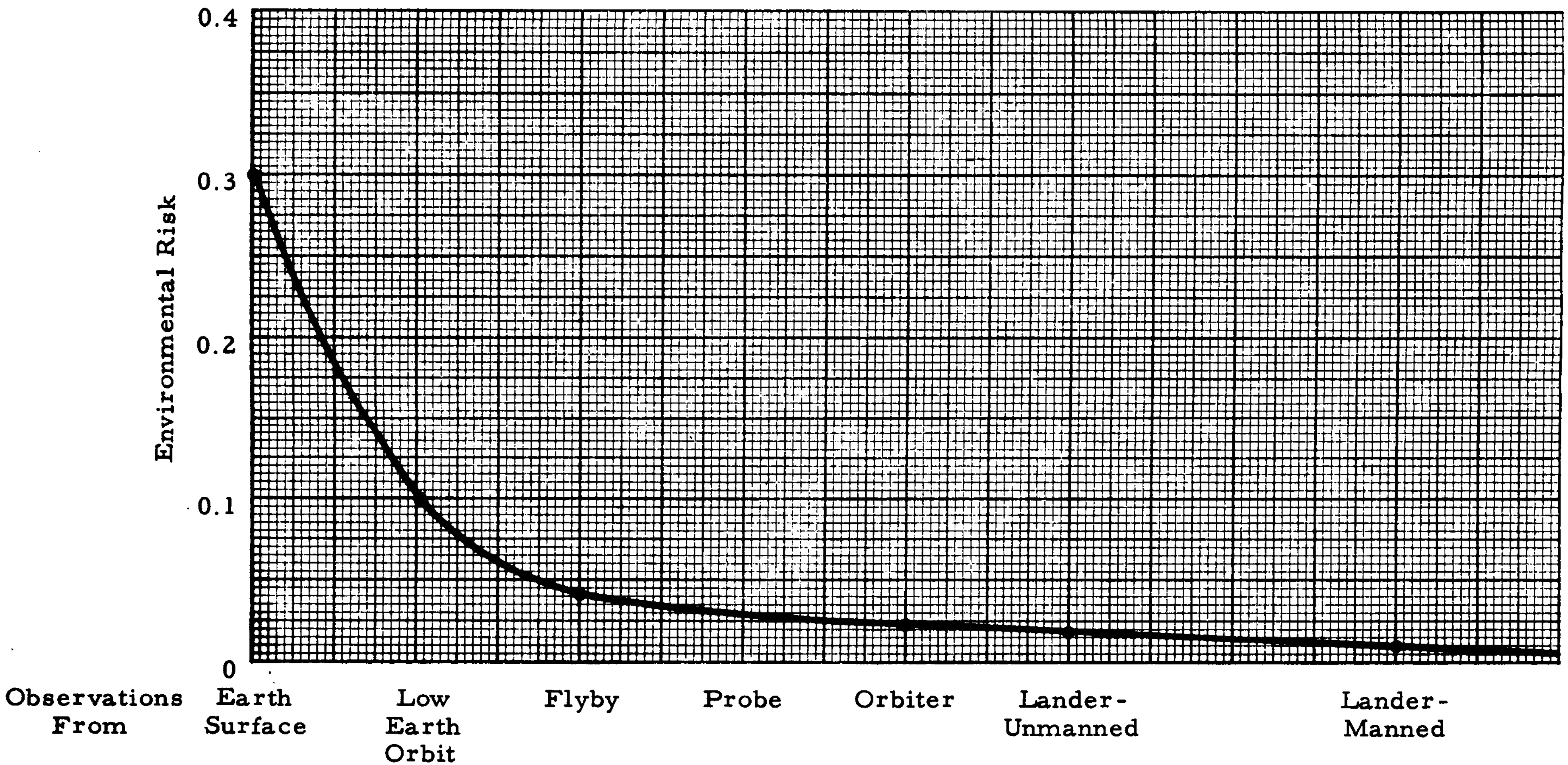


EXHIBIT 28 - SPACECRAFT COMBINED SYSTEMS TESTING RISK



Level of Knowledge of Environment Near a Particular Planet Based on Prior Successful Observations

EXHIBIT 29 - ENVIRONMENTAL RISK

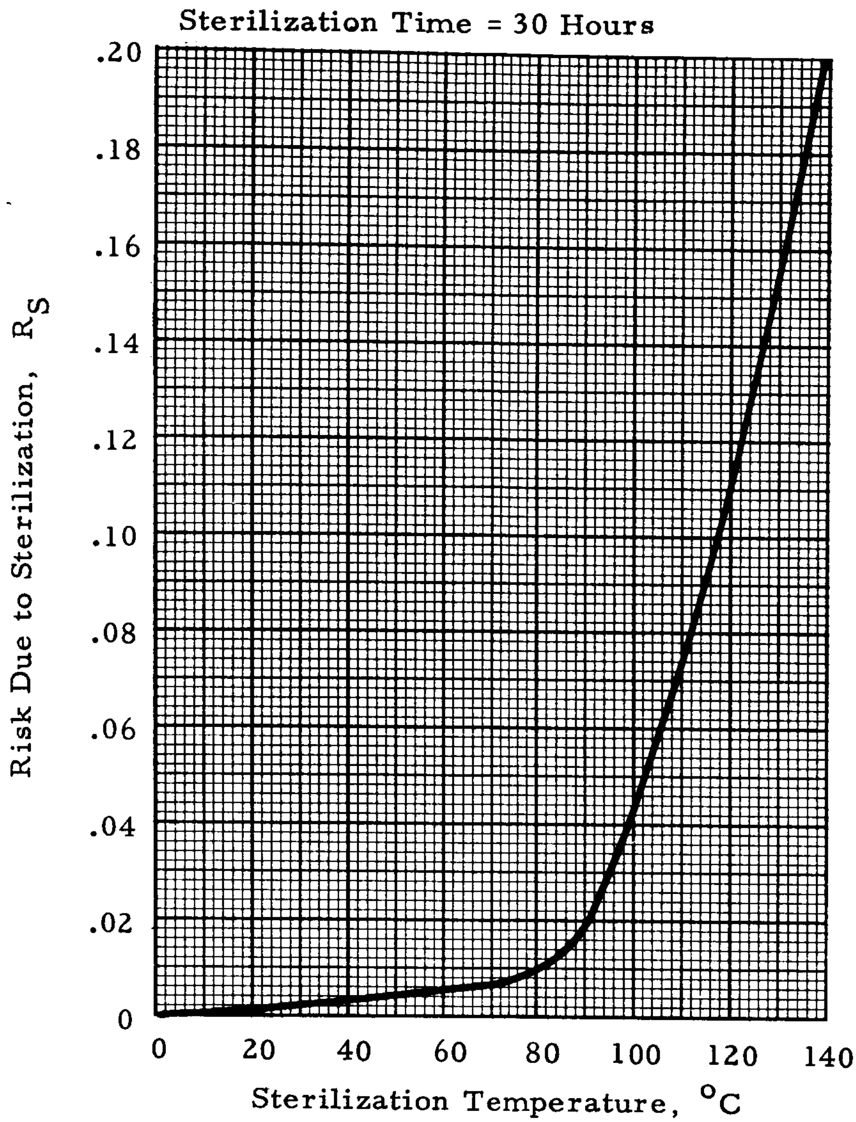


EXHIBIT 30 - STERILIZATION INTENSITY RISK

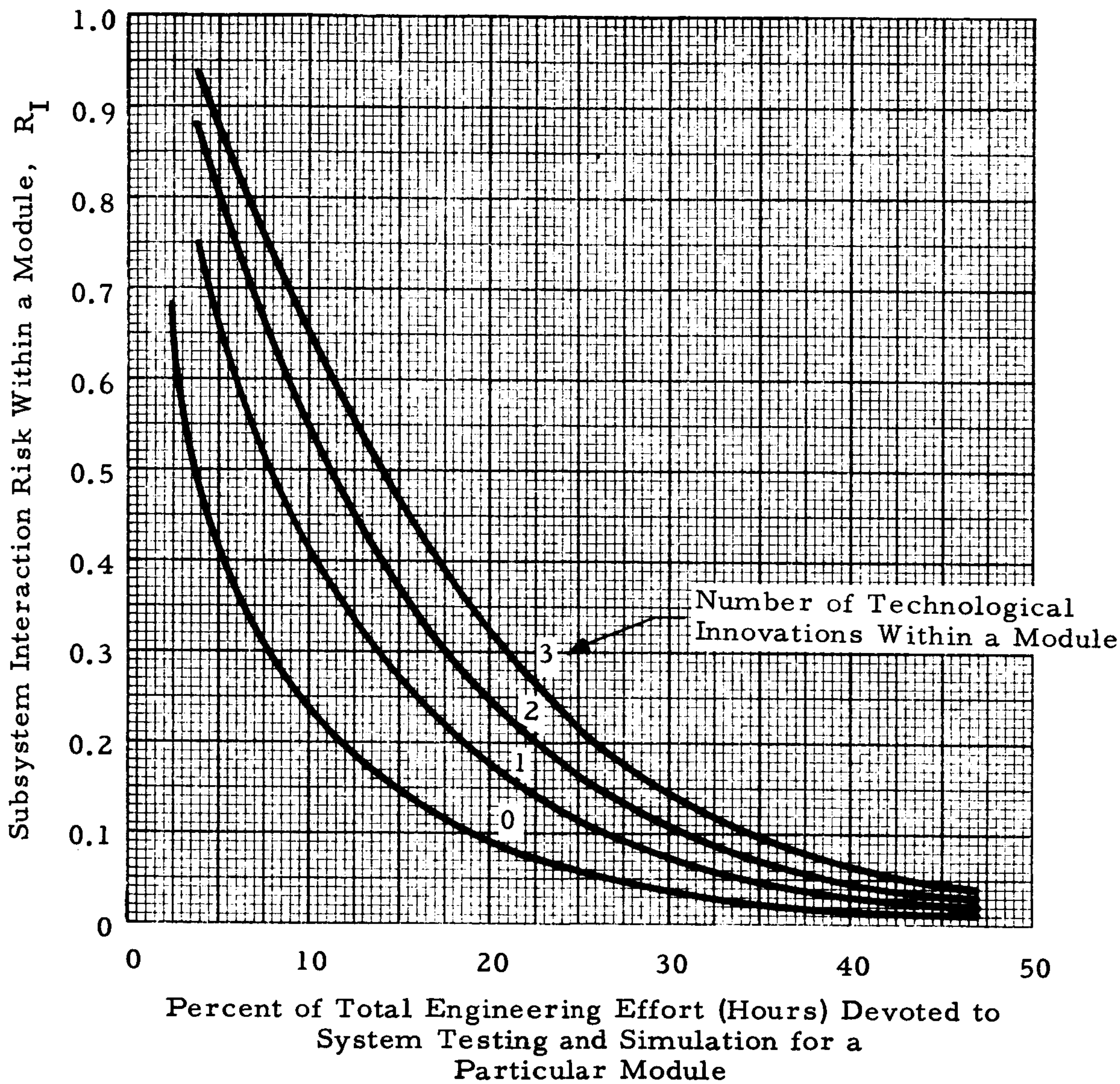


EXHIBIT 31 - SUBSYSTEM INTERACTION RISK WITHIN A MODULE

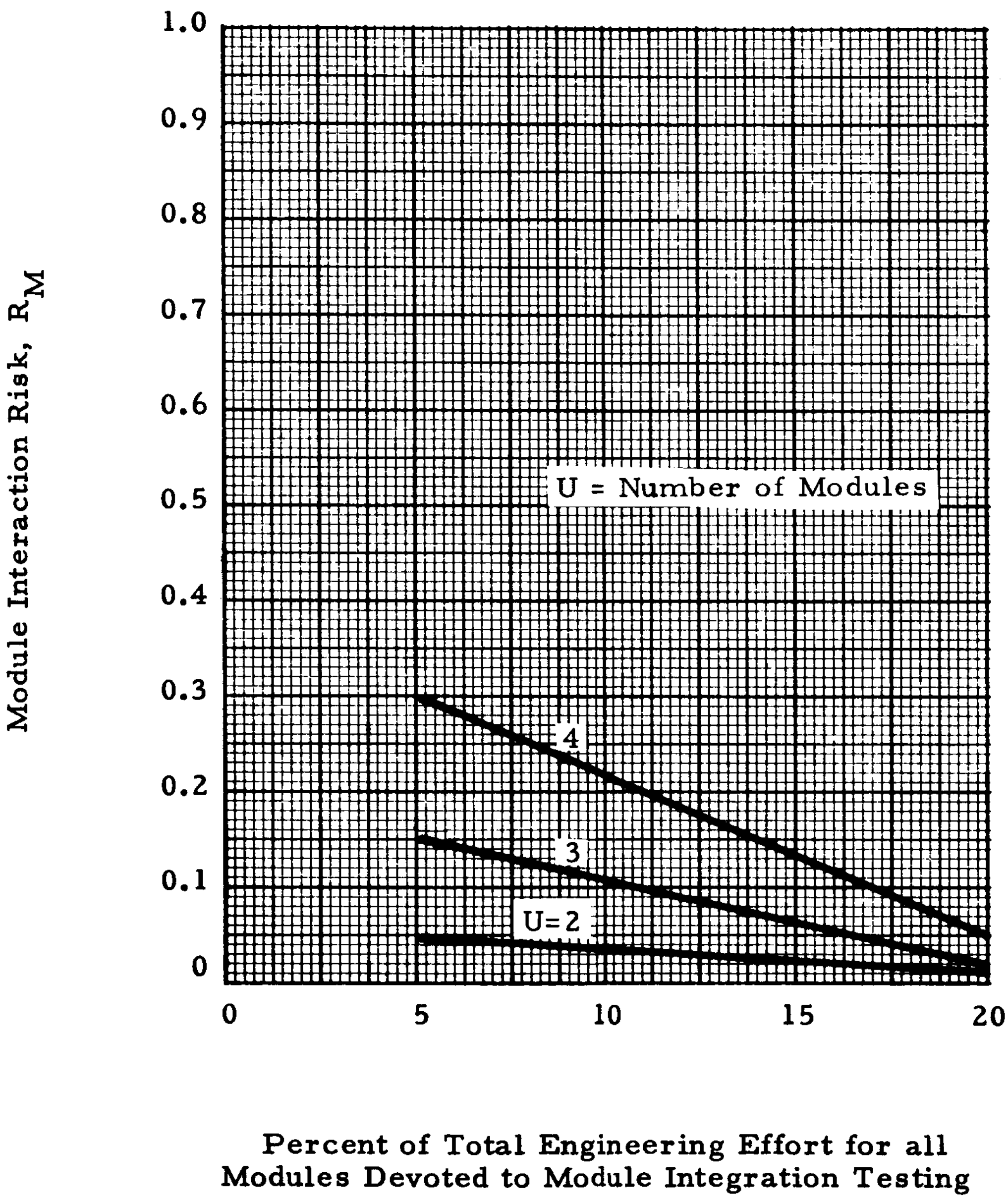


EXHIBIT 32 - MODULE INTERACTION RISK

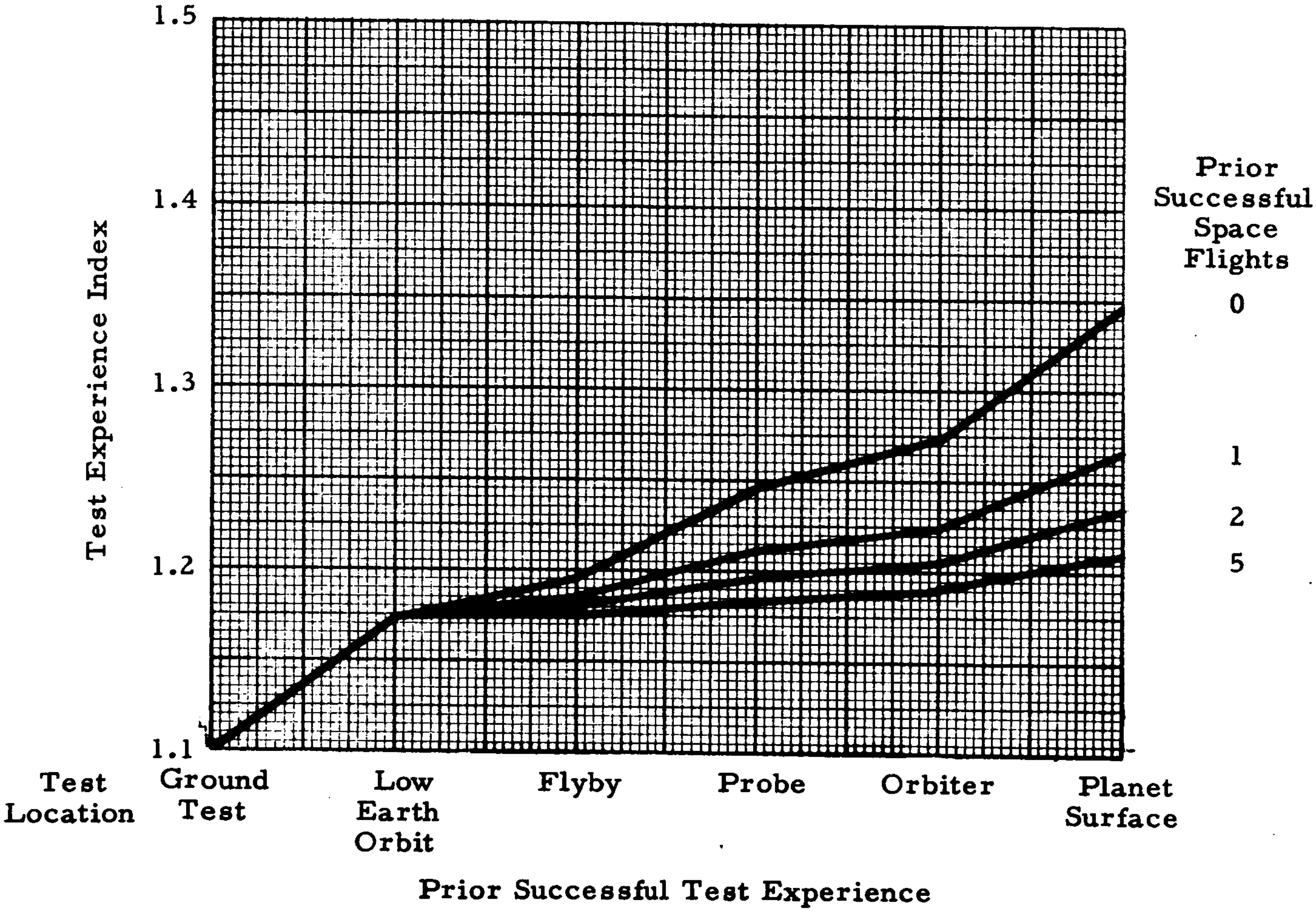


EXHIBIT 33 - TEST PLAN RISK

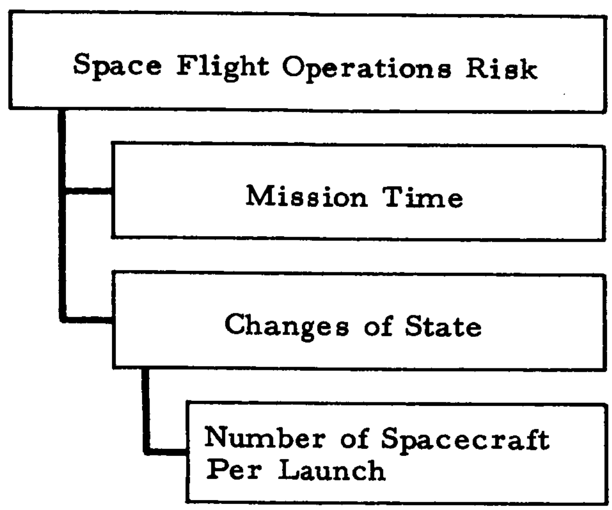


EXHIBIT 34 - SPACE FLIGHT OPERATIONS RISK

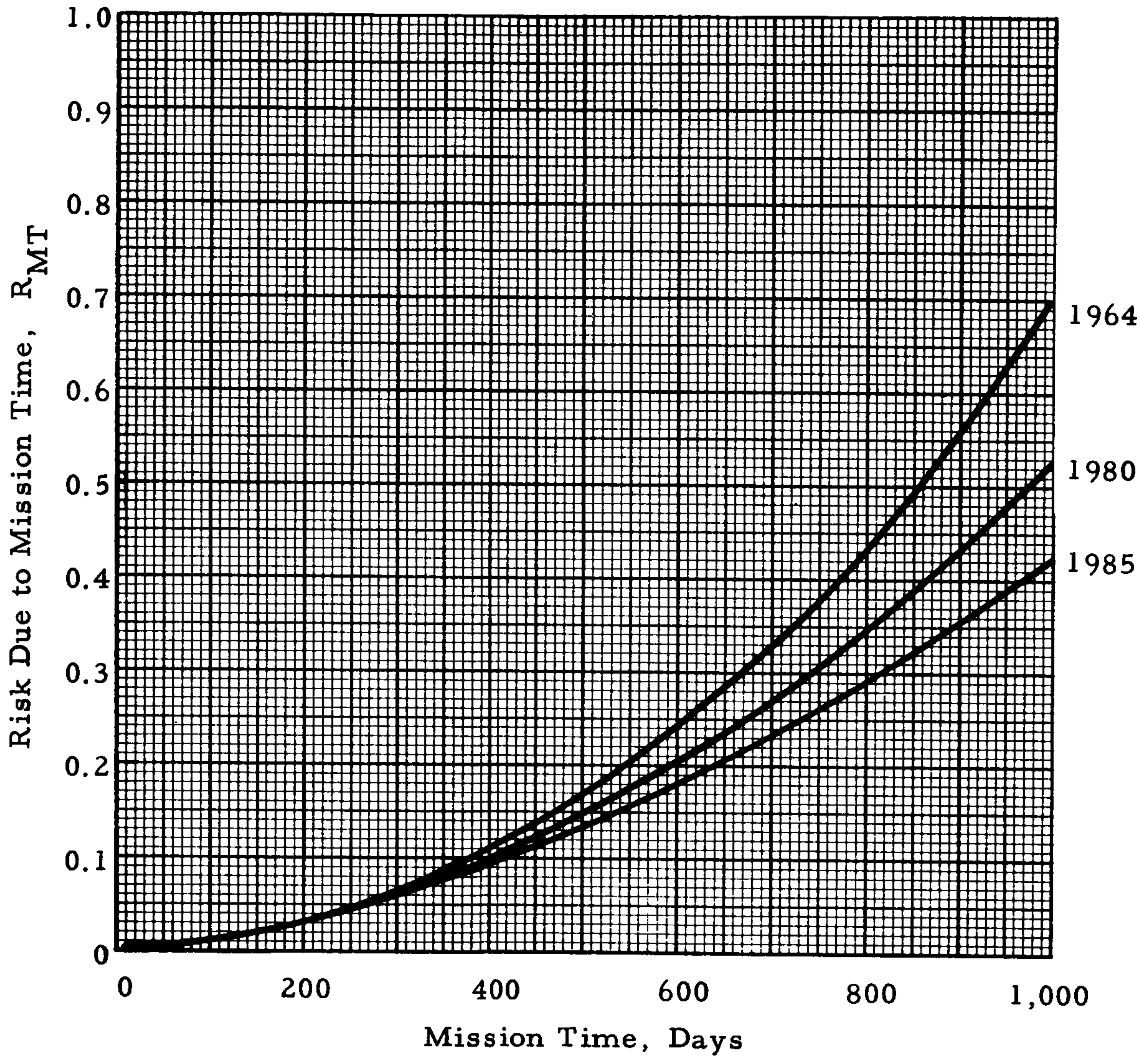


EXHIBIT 35 - RISK DUE TO MISSION TIME

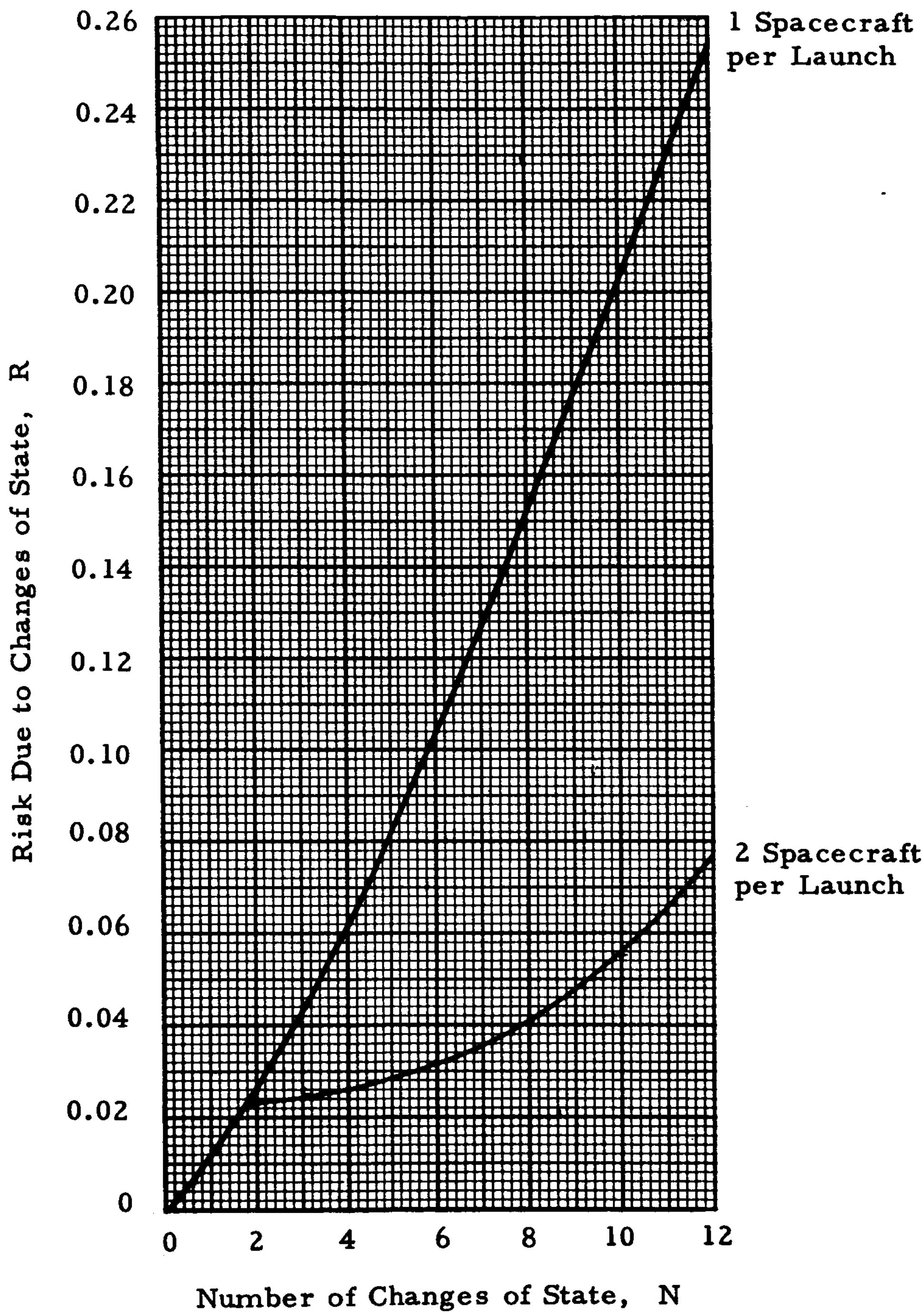


EXHIBIT 36 - RISK DUE TO CHANGES OF STATE

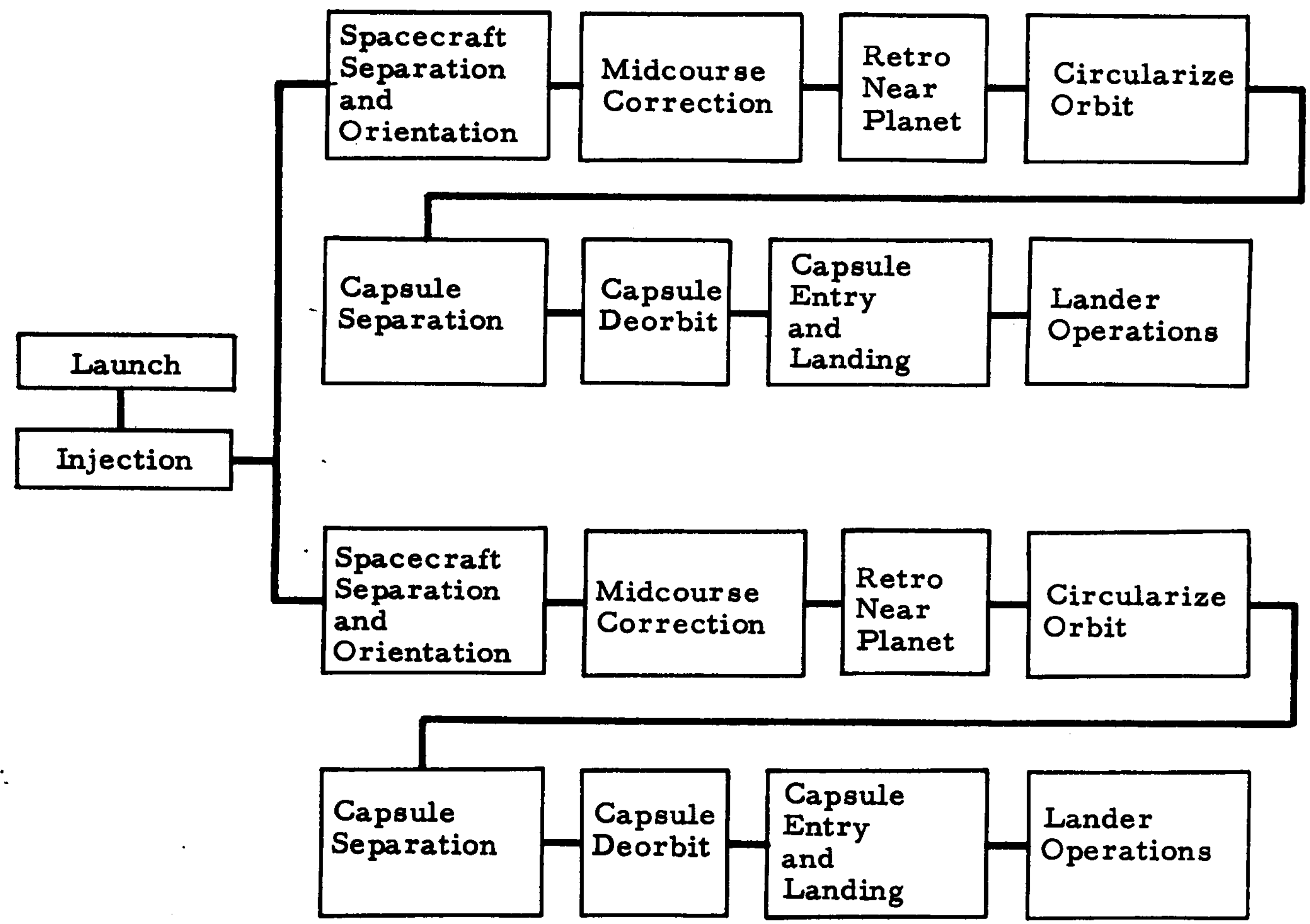


EXHIBIT 37 - ILLUSTRATION OF CHANGES OF STATE IN SPACE FLIGHT OPERATIONS FOR TWO SPACECRAFT PER LAUNCH VEHICLE

MISSION: Mariner IV

MISSION DESIGN RISK					
Risk Category	Inputs	RER Exhibit	Operations	Risk: 1st Launch	Risk: 2nd Launch
Schedule	N = .8 Number of Spacecraft for Launch = 2	2	1	.16	.16
Nonspacecraft Technological Innovations	Shroud/Ground Test — Backup: No; I: 1; T: 1; R: .20 (1) 2 3 4	3	1 - (1 - $\boxed{1}$) ··· (1 - $\boxed{4}$). 2	.20	0*
Operational Mode Complexity	Mode fly-by G. A. R. 5000 km Command Override Yes/~~No~~	5	3	.06	.06
Summary MD	--	--	1 - (1 - 1) (1 - 2) x (1 - 3)	.36	.21

*Risk removed by development efforts for first launch (1L).

EXHIBIT 38

MISSION: **Mariner IV**

SUBSYSTEM DESI

Risk Category	Inputs	Backup	I	T
Spacecraft Technological Innovations	Canopus sensor	No	1	1
	Lightweight structure	Yes		
	Communications	Yes	3	1
	Data management	Yes		
Structure Propulsion Navigation and Guidance Attitude Stabilization and Control Communications Data Management Electrical Power Descent Systems				

Risk Category	Inputs	W	$\boxed{1}$ OMI_R	$\boxed{2}$ OMI_D	$\boxed{3}$ $\boxed{2}$ / $\boxed{1}$	Risk
Experiments	5 fly-by	1	1.22	1.22	1.00	0
	5 gnd test	1	1.22	1.10	.90	
	n = 10					
$Summary_{SBD}$						

EXHIB

GN AND DEVELOPMENT

Risk		RER Exhibit	Operations	Risk: 1st Launch	Risk: 2nd Launch
.200	1	7 and 8	Risk = 1 - (1 - $\boxed{1}$)(1 - $\boxed{2}$) . . . (1 - $\boxed{5}$)	.31	0*
	2				* risk removed by dev. for 1L
.135	3				
	4				
	5		1		
0	1		Risk = 1 - (1 - $\boxed{1}$)(· · ·)(1 - $\boxed{8}$)	0	0
0	2				
0	3				
0	4				
0	5				
0	6				
0	7				
0	8		2		
= 1 - $\boxed{3}$	3		$R_{EX} = \sum_{i=1}^{i=n} \frac{WR_i}{n}$	.05	.05
.100	$\boxed{4}$ $\boxed{5}$ $\boxed{6}$ $\boxed{7}$ $\boxed{8}$		$= \frac{5 \times 1 \times .1 + 5 \times 1 \times 0}{10}$ 3		
			R_{SBD} = 1 - (1 - 1)(1 - 2)(1 - 3) (1L) = 1 - (1 - .31)(1 - .05)	.345	.05

IT 39

MISSION: Mariner IV

COMBINED SYSTE

Risk Categories	Inputs				
Environmental Knowledge (R_{EN})	Level of Knowledge Low earth orbit				
Sterilization Intensity (R_{SI})	Sterilization Temperature None °C				
Subsystem Interaction (R_{SSI})	Percent Total Engr. Effort Devoted to System Testing and Simulation Per Module 35	Modules	I/M	Risk	1 2 3 4 * ente
		one	2* equiv.	--	
Module Interaction (R_{NI})	Percent of Total Engr. Effort--All Modules Devoted to Module Testing 0	Number of Modules = 1			
Test Plan Risk (R_{TP})		Modules	Prior Test Experience	1 TEIR	2 TEI
		one	gnd test	1.195	1.1

Summary

Combined Systems Testing Risk (R_{CST})	______________		

$R_{CST} = 1 - (1 - R_{EN})(1 - R_{SI}$

$= 1 - (1 - ①)(\cdot\cdot\cdot)(1 -$

EXHIBIT

Operations					RER Exhibit	Launch Risk	
						1st Launch	2nd Launch
1					29	.10	.10
2					30	0	0
Risk = 1 - (1 - $\boxed{1}$)(· · ·)(1 - $\boxed{4}$) r Exhibit 7 with .31 obtained from Exhibit 39. 3					31	.07	.07
4					--	--	--
)	$\boxed{3}$ No. of Flights	$\boxed{4}$ $\boxed{2}$ / $\boxed{1}$	$\boxed{5}$ Risk = 1 - $\boxed{4}$	R = 1 - (1 - $\boxed{6}$)(· · ·)(1 - $\boxed{9}$)			
)	0	.92	.08	$\boxed{6}$ $\boxed{7}$ $\boxed{8}$ $\boxed{9}$ 5	33	.08	.08
					--	.23	.23

$)(1 - R_{SSI})(1 - R_{MI})(1 - R_{TP})$

5) = 1 - (1 - .10)(1 - .07)(1 - .08) = .23

40

64-2

SPACE FLIGHT OPERATIONS RISK

Risk Categories	Inputs	RER Exhibit	Launch Risk	
			1st Launch	2nd Launch
Mission Time (R_{MT})	Mission Time 225 Days Year 1964	35	.05	.05
Changes of State (R_{CS})	Number of Changes of State 5 Number of Spacecraft Per Launch 1	36	.08	.08

Summary

Space Flight Operations Risk (R_{SFO})	--	--	.125	.125

$$R_{SFO} = 1 - (1 - R_{MT})(1 - R_{CS}) = 1 - (1 - .05)(1 - .08)$$

Mission Risk Summary (R_P)

Risk Categories	Launch Risk	
	1st Launch	2nd Launch
Mission Design (R_{MD})	.360	.210
Subsystem Design and Development (R_{SBD})	.345	.050
Combined Systems Testing (R_{CST})	.230	.230
Space Flight Operations (R_{SFO})	.125	.125

Mission Risk Summary (R_P)	.72	.50

$$R_P = 1 - (1 - R_{MD})(1 - R_{SBD})(1 - R_{CST})(1 - R_{SFO})$$

EXHIBIT 41

MISSION: **Mariner IV**

Mission Design Risk

System Design(1)

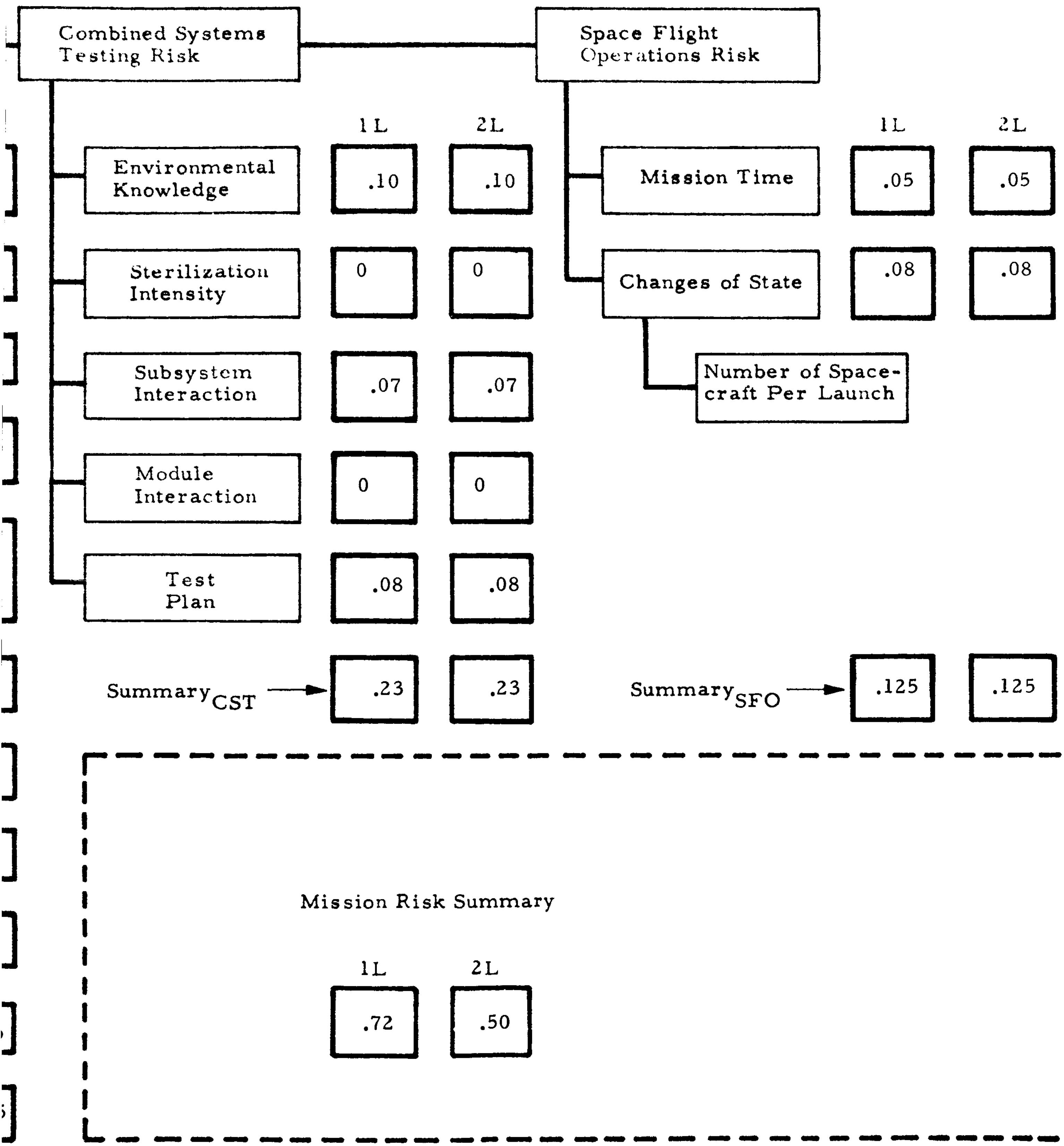
- DC_1 Atlas Agena LV;
- DC_2 two launches
- DC_i

	1L	2L
Schedule	.16	.16
Nonspacecraft Technological Innovations	.20	0
Operational Mode Innovations	.06	.06
$Summary_{MD}$ →	.36	.21

Subsystem Design and Development Risk

	1L	2L
Spacecraft Technological Innovations	.31	0
Structure	0	0
Propulsion	0	0
Navigation and Guidance	0	0
Attitude Stabilization and Control	0	0
Communications	0	0
Data Management	0	0
Electrical Power	0	0
Descent Systems	0	0
Experiments	.05	.0
$Summary_{SBD}$ →	.345	.0

Note: (1) Input only.


Combined Systems Testing Risk
Space Flight Operations Risk
1L
2L
Environmental Knowledge
.10
.10
Sterilization Intensity
0
0
Subsystem Interaction
.07
.07
Module Interaction
0
0
Test Plan
.08
.08
Summary$_{CST}$
.23
.23
1L
2L
Mission Time
.05
.05
Changes of State
.08
.08
Number of Spacecraft Per Launch
Summary$_{SFO}$
.125
.125
Mission Risk Summary
1L
2L
.72
.50

MISSION: Mars Orbiter/Lander

MISSION DESIGN RISK					
Risk Category	Inputs	RER Exhibit	Operations	Risk 1st Launch	Risk 2nd Launch
Schedule	N = 1 Number of Spacecraft for Launch = 2	2	(1)	.10	.10
Nonspacecraft Technological Innovations	None / Backup / I / T / R — rows 1, 2, 3, 4	3 and/or 4	$1 - (1 - \boxed{1}) \cdots (1 - \boxed{4})$ (2)	0	0
Operational Mode Complexity	Mode orbiter G. A. R. 4000 km Command Override Yes/~~No~~	5	(3)	.06	.06
Summary MD	--	--	$1 - (1 - 1)(1 - 2) \times (1 - 3)$ $1 - (1 - .10)(1 - .06)$	.15	.15

EXHIBIT 43

MISSION: Mars Orbiter/Lander

SUBSYSTEM DESIGN

Risk Category	Inputs						
Spacecraft Technological Innovations		Backup	I	$\overline{T}$			
	Sterilizable batteries (capsule)	No	3	1.5			
	Descent propulsion (capsule)	No					
	Entry capsule	No					
	Propulsion module	Yes	1	2			
Structure Propulsion Navigation and Guidance Attitude Stabilization and Control Communications Data Management Electrical Power Descent Systems							
Experiments		Test Exp	W	[1] OMI_R	[2] OMI_D	[3] [2] / [1]	Risk =
	ABL/	gnd test	2	1.48	1.10	.74	.26
	Orbiter TV/	fly-by	2	1.27	1.22	.96	.04
	8 minor surface experiments/	fly-by	1	1.48	1.22	.82	.18
		n = 10					
$Summary_{SBD}$							

EXHIBIT

AND DEVELOPMENT

Risk		RER Exhibit	Operations	Risk 1st Launch	Risk 2nd Launch
Risk		7 and 8	Risk = $1 - (1 - \boxed{1})(1 - \boxed{2}) \cdots (1 - \boxed{5})$	.27	0*
	1				* risk removed by dev. for 1L
.265	2				
	3				
.005	4				
	5		1		
0	1		Risk = $1 - (1 - \boxed{1})(\cdots)(1 - \boxed{8})$	0	0
0	2				
0	3				
0	4				
0	5				
0	6				
0	7				
0	8		2		
1 - $\boxed{3}$		27	$R_{EX} = \sum_{i=1}^{i=n} \frac{WR_i}{n}$	.20	.19*
	$\boxed{4}$				* risk reduced by successful orbiter TV on 1L
	$\boxed{5}$				
	$\boxed{6}$				
	$\boxed{7}$				
	$\boxed{8}$		3		
			$R_{SBD} = 1 - (1 - ①)(1 - ②)(1 - ③)$	.42	.19

MISSION: Mars Orbiter/Lander

COMBINED SYST

Risk Categories	Inputs						
Environmental Knowledge (R_{EN})	Level of Knowledge Prior probe						
Sterilization Intensity (R_{SI})	Sterilization Temperature 135 °C x 30 hours						
Subsystem Interaction (R_{SSI})	Percent Total Engr. Effort Devoted to System Testing and Simulation Per Module 30 All modules	Modules		I/M	Risk		
		propulsion		1	.08	1	
		orbiter		0	.04	2	
		capsule		3	.15	3	
		ABL		1	.08	4	
						* I a	
Module Interaction (R_{NI})	Percent of Total Engr. Effort--All Modules Devoted to Module Testing 10	Number of Modules = 4				* F a	
Test Plan Risk (R_{TP})		Modules	Prior Test Experience			1 TEIR	2 TEI
		propulsion	E. O. equiv.			1.27/1.22	1.18/1
		orbiter	Gnd test			1.27/1.22	1.10/1
		capsule	Atm. test			1.35/1.35	1.14/1
		ABL	Gnd test			1.35/1.35	1.10/1

Summary

Combined Systems Testing Risk (R_{CST})	______		

$R_{CST} = 1 - (1 - R_{EN})(1 - R_{S}$

$= 1 - (1 - 1)(\ldots)(1 -$

EXHIB

Operations	RER Exhibit	Launch Risk 1st Launch	Launch Risk 2nd Launch
①	29	.03	.025
②	30	.18	.18
Risk = 1 - (1 - $\boxed{1}$)(· · ·)(1 - $\boxed{4}$) isk reduced by successful operation of propulsion nd orbiter modules on 1L. ③	31	.31	.22*
isk reduced by successful operation of propulsion nd orbiter modules on 1L. ④	32	.22	.04*
(see sub-table below) ⑤	33	.46	.32
	--	.77	.59

)	$\boxed{3}$ No. of Flights	$\boxed{4}$ $\boxed{2}$ / $\boxed{1}$	$\boxed{5}$ Risk = 1 - $\boxed{4}$	R = 1 - (1 - $\boxed{6}$)(· · ·)(1 - $\boxed{9}$)
.22	0/1	.93/1	.07/0	$\boxed{6}$
.22	0/1	.86/1	.14/0	$\boxed{7}$
.14	0/0	.84/.84	.16/.16	$\boxed{8}$
.10	0/0	.81/.81	.19/.19	$\boxed{9}$

$(1 - R_{SSI})(1 - R_{MI})(1 - R_{TP})$

⑤)

T 45

64-2

SPACE FLIGHT OPERATIONS RISK

Risk Categories	Inputs	RER Exhibit	Launch Risk	
			1st Launch	2nd Launch
Mission Time (R_{MT})	Mission Time(210+90) 300 Days Year 1973, 1975	35	.07	.07
Changes of State (R_{CS})	Number of Changes of State 10 Number of Spacecraft Per Launch 2	36	.055	.055

Summary

Space Flight Operations Risk (R_{SFO})	--	--	.12	.12

$$R_{SFO} = 1 - (1 - R_{MT})(1 - R_{CS}) = 1 - (1 - .07)(1 - .055)$$

Mission Risk Summary (R_P)

Risk Categories	Launch Risk	
	1st Launch	2nd Launch
Mission Design (R_{MD})	.15	.15
Subsystem Design and Development (R_{SBD})	.42	.19
Combined Systems Testing (R_{CST})	.77	.59
Space Flight Operations (R_{SFO})	.12	.12

Mission Risk Summary (R_P)	.90	.75

$$R_P = 1 - (1 - R_{MD})(1 - R_{SBD})(1 - R_{CST})(1 - R_{SFO})$$

EXHIBIT 46

MISSION: Mars Orbiter/Lander

Mission Design Risk

System Design (1)

- DC_1
- DC_2
- DC_i

Saturn V LV; 2 launches, dual spacecraft per launch

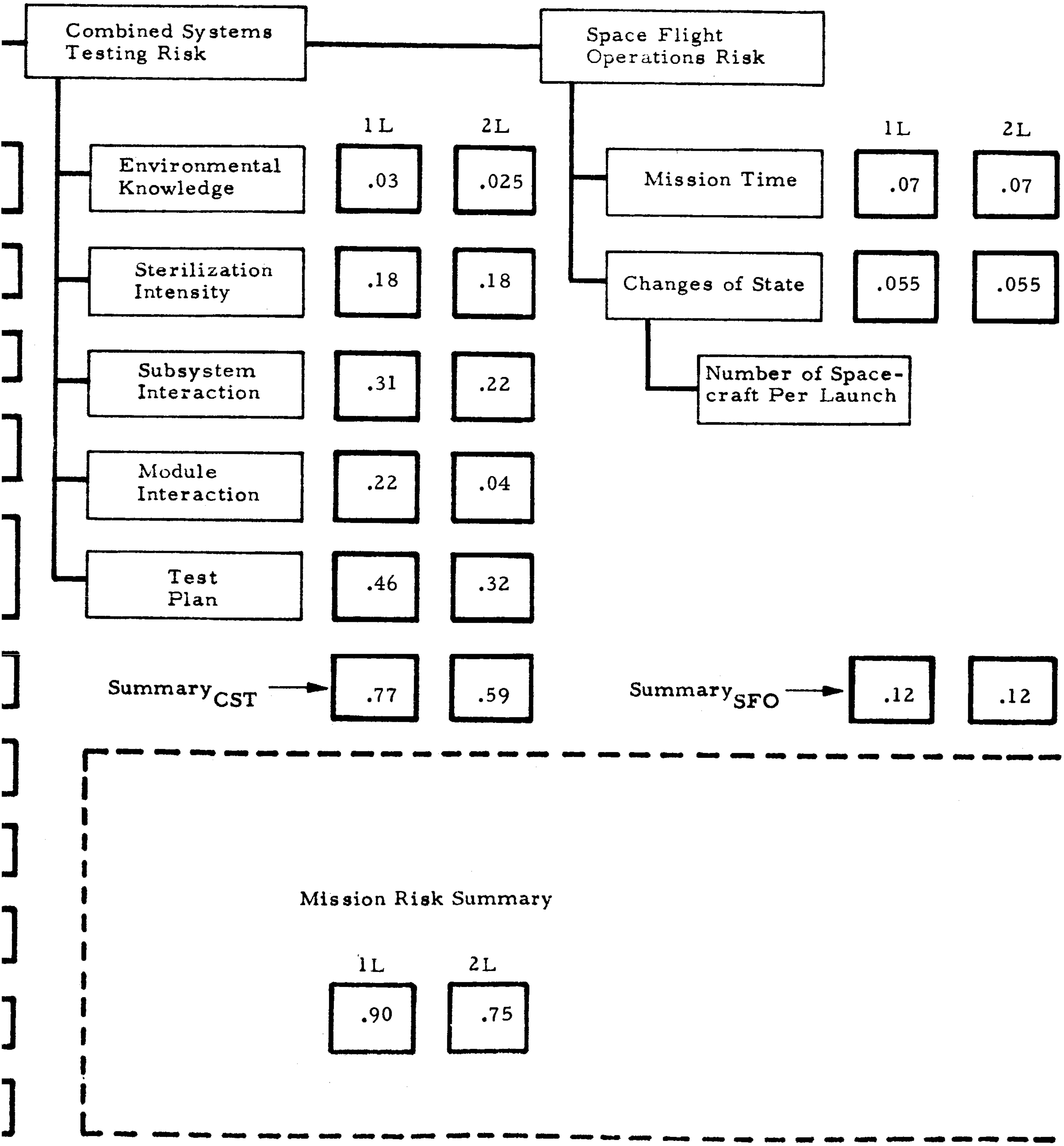
	1L	2L
Schedule	.10	.10
Nonspacecraft Technological Innovations	0	0
Operational Mode Innovations	.06	.06
Summary$_{MD}$ →	.15	.15

Subsystem Design and Development Risk

	1L	2L
Spacecraft Technological Innovations	.27	0
Structure	0	0
Propulsion	0	0
Navigation and Guidance	0	0
Attitude Stabilization and Control	0	0
Communications	0	0
Data Management	0	0
Electrical Power	0	0
Descent Systems	0	0
Experiments	.20	.19
Summary$_{SBD}$ →	.42	.19

Note: (1) Input only.

EXHI


Combined Systems Testing Risk
Space Flight Operations Risk
1L
2L
Environmental Knowledge
.03
.025
Sterilization Intensity
.18
.18
Subsystem Interaction
.31
.22
Module Interaction
.22
.04
Test Plan
.46
.32
Summary$_{CST}$
.77
.59
1L
2L
Mission Time
.07
.07
Changes of State
.055
.055
Number of Spacecraft Per Launch
Summary$_{SFO}$
.12
.12
Mission Risk Summary
1L
2L
.90
.75

REFERENCES

1. Hoffman, F. E., et al., Risk Technique Study--Monthly Progress Report Number Three, Planning Research Corporation, PRC D-1411, 15 March 1967

2. Hoffman, F. E. et al., Development of Cost Estimating Techniques and Relationships for Unmanned Space Exploration Missions, Planning Research Corporation, PRC R-870, 28 October 1966

3. Sohn, R. L., "Venus Swingby Mode for Manned Mars Missions," Journal of Spacecraft and Rockets, Vol. I, No. 5, September-October 1964

4. Breakwell, J. V., L. F. Helgostam, and M. A. Krop, "Guidance Phenomena for a Mars Missions," Advances in the Astronautical Sciences, Vol. 15, American Astronautical Society Publication, June 1963

5. Gerard, G., Introduction to Structural Stability Theory, McGraw-Hill, Inc., 1962

6. Sandorff, P. E., "Structures Considerations in Design for Space Boosters," ARS Journal, November 1960

7. Kotanchik, J. N., and R. B. Erb, "Structures and Materials for Manned Reentry Vehicles," AIAA Paper No. 66-987, presented at AIAA Annual Meeting, Boston, Massachusetts, 29 November 1966

8. Hoff, N. J., "Thin Shells in Aerospace Structures," AIAA Paper No. 66-1022, presented at AIAA Annual Meeting, Boston, Massachusetts, 29 November 1966

9. Sutton, G. P., "Rocket Propulsion Systems for Interplanetary Flight," Journal of Institute of Aeronautical Sciences, Vol. 26, October 1959

10. Kaufman, M. H., and R. B. Leipnik, "The Fallacy of a Figure of Merit for Rocket Propellants," Chemical Engineering Progress Vol. 59, No. 9, September 1963

11. Haynes, N. R., et al., "Mariner 4 Flight Path to Mars," Astronautics and Aeronautics, June 1965

12. Bartholomew, C. S., and D. C. Porter, "Reliability and Sterilization," Paper presented at AIAA/AAS Stepping Stones to Mars Meeting, Baltimore, Maryland, 28 March 1966

13. King, C. M., A Stabilization and Control System for an Interplanetary Space Vehicle, Avco Corporation (Nasw 607)

14. Jet Propulsion Laboratory, Technical Report No. 32-1023, Surveyor 1 Mission Report, Part 1, Mission Description and Performance

15. Jet Propulsion Laboratory, The Mariner Mission, 1962

16. Yamauchi, T. T., An Adaption of Lunar Orbitor for Orbital Reconnaissance of Mars, Conference Record--1967 Winter Convention on Aerospace and Electronic Systems, Vol. VI

17. Mariner Mars 1964 Telecommunications System, Jet Propulsion Laboratory, Technical Report 32-836, 1 December 1965 (N66-26866)

18. Jet Propulsion Laboratory, Space Programs Summary No. 37-38, Vol. III: "The Deep Space Network," 31 March 1936

19. Thompson Ramo Wooldridge, Pioneer System Capabilities, 1966

20. Jet Propulsion Laboratory, TR 32-1023, Surveyor I Mission Report, Part II: Scientific Data and Results, 10 September 1966

21. Armour Research Foundation, RADC-TR-60-97A, B, Methods of Comparison and Evaluation of Communication Systems (Vols. I and II) 31 March 1960

22. R. F. Miles, Mariner 1964 Spacecraft Functional Description, Jet Propulsion Laboratory, EPD 277, Rev. 1., 8 February 1966

23. Liviakis, G., A Survey of Spaceborne Computers, Planning Research Corporation, PRC D-1237, 27 June 1966

24. Szego, G. C., "Space Power Systems State-of-the-Art" Journal of Spacecraft and Rockets, Vol. 2, No. 5, September-October 1965, pp. 641-659

25. National Aeronautics and Space Administration, Electrical Power Generation Systems for Space Applications, 1965 (SP-79)

26. Flanigan, Nichol, and Wood, Study of Satellite Attitude Control and Related Energy Sources, General Electric Company, Technical Documentary Report, No. ASD-TDR-63-179, May 1963

27. Szego and Taylor, Progress in Astronautics and Aeronautics, Volume 16: Space Power Systems Engineering, Academic Press, 1966

28. Snyder, Progress in Astronautics and Aeronautics, Volume 4: Space Power Systems, Academic Press, 1961

29. Snyder, Progress in Astronautics and Aeronautics, Volume 3: Energy Conversion for Space Power, Academic Press, 1961

30. Padwo, "The Battery, A State-of-the-Art Survey," Yardney Electric Corporation, Electrical Design News, January 1963

31. Rappaport, P., "Space Power: The Next Step," Space/Aeronautics, September 1965, pp. 76-83

32. Klass, "Thin-Film Solar Cells Boost Output Ratio," Aviation Week/Space Technology, 29 November 1965

33. Jet Propulsion Laboratory, Voyager Project Study--Presentation to NASA, 14 September 1966

APPENDIX

ELECTRICAL POWER REFERENCES

Hanna, J., Nuclear Auxiliary Power Systems, The Boeing Company, D2 90275, 24 June 1964

Westmoreland, L. Q., Power Subsystems State of the Art and Projection Report, Douglas Missile and Space Systems Division, SM-52024, Contract AF 04(695)-953, April 1966

Carpenter, R. T., "U.S. Atomic Energy Commission Isotopic Power Applications," Proceedings of the American Nuclear Society National Topical Meeting, 21-23 March 1966, Augusta, Georgia, Savannah River Laboratory Report DP-1066, Vol. 1, pp. V-3 to V-16

Lafleur, Dr. J. D. and R. T. Carpenter, "The Nuclear Space Power Program," Paper presented at the 12th Nuclear Science Symposium, San Francisco, California, 18 October 1965

Finger, H. B., "Nuclear Space Program: Organization and Plans," Atomic Industrial Forum Twelfth Annual Conference, Washington, D.C., 17 November 1965

Elias, D. and H. Gray, "Advanced Radioisotpoe Thermoelectric Space Power System," SAE paper 650792, 8 October 1965

Elias, D. and H. Gray, Systems for Nuclear Auxiliary Power, USAEC Report TID-20103, 1964

Stromer, P. R., Auxiliary Power Systems for Spacecraft--An Annotated Bibliography, May 1963 (AD-423714)

Stromer, P. R., NASA Pattern Relevance Guide, Volume III: Technology Document, Honeywell, Military Products Group Aeronautical Division, Aeronautics Report 8-20207RG, NASA Contract NAS 8-20207

Stewart, D. H., G. M. Anderson, et al., Systems for Nuclear Auxiliary Power--An Evaluation, USAEC Report TID-20079, 1964

Mahefkey, E. T., Jr. and D. F. Berganini, "Radioisotope Power Subsystems for Space Application," SAE paper 650791, 8 October 1965

Mahefkey, E. T., Jr. and D. F. Berganini, Design and Analysis of an Isotope Dynamic Power System for Prolonged Missions Apollo (Apollo X, AORL), Atomics International, AI-65-20

Mahefkey, E. T., Jr. and D. F. Berganini, Application of Nuclear Power Plants (SNAP Units) to the Manned Orbiting Research Laboratory (MORL), Atomics International, NAA-SR-10318

Mahefkey, E. T., Jr. and D. F. Berganini, A 1.7 KWE Radioisotope Thermoelectric Power System for Use in Manned and Unmanned Space Missions, Atomics International, AI-MEMO-64-55, Vol. 1, May 1964

McNab, I. R., "Power Conversion in Space," Paper presented at the I.E.E. Colloquium on "Electrical Methods of Propulsion in Space," London, 13 February 1964

McNab, I. R., Study and Analysis of Satellite Power Systems Configurations for Maximum Utilization of Power, TRW Systems Group, TRW 04898-6001-R00, 30 December 1966, NASA Contract NAS 5-9178 with Goddard Space Flight Center

Cherry, W. and J. A. Zoutendyk, "The State of the Art in Solar Cell Arrays for Space Electrical Power," AIAA paper 64-738, September 1964

Szeqo, G. C., "Space Power Systems State of the Art," Journal of Spacecraft and Rockets, Vol. 2, No. 5, September 1965

DuPont, P. S., "Syncom Electrical Power System," Journal of Spacecraft and Rockets, Vol. 3, No. 4, April 1966

MacKenzie, C. M., et al., "Nimbus Power Systems," Supplement to IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-2, No. 6, November 1966

Bernatowicz, D. T., et al., "Solar and Chemical Power Systems," Space/Aeronautics, R&D Issue, 1966

Bernatowicz, D. T., et al., Large Area Solar Array Design--First Quarterly Report, Volume 1, The Boeing Company, 02-113355-1, January 1967

Bernatowicz, D. T., et al., Proceedings of the Fifth Photovoltaic Specialists Conference, PIC-SOL 20916, December 1965

Bernatowicz, D. T., et al., Development of Lightweight Rigid Solar Panel, Electro-Optical Systems, Inc., EOS Report 7027-IDR Interim Design Report, NASA Contract NAS7-428

Cherry, W. R. and L. W. Slifer, Jr., "Advanced Solar Cell Power Systems for Space," Paper presented at the 19th Annual Power Sources Conference, Atlantic City, New Jersey, 20 May 1965

Cherry, W. R., "Status of Photovoltaic Solar Energy Converters," IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-1, No. 1, August 1965

Slifer, L. W., Jr., et al., Characteristics of the Solar Arrays for the Energetic Particle Explorers, National Aeronautics and Space Administration, Goddard Space Flight Center, X-716-65-392, October 1965

Moses, E., The Atmosphere Explorer-B Solar Array (AE-B), National Aeronautics and Space Administration, Goddard Space Flight Center, X-716-65-401, October 1965

Gruntz, R. D. and R. A. Rackley, "SNAP 50/SPUR Power Conversion System Objectives, Current Status, and Lunar Applications," Conference Proceedings, SAE 1965 Aerospace Fluid Power Systems and Equipment Conference, May 1965

Gruntz, R. D. and R. A. Rackley, Preliminary Evaluation of Reactor Power Systems for Manned Orbiting Space Station, Atomics International, NAA-SR-MEMO-9550, 19 February 1964

Gruntz, R. D. and R. A. Rackley, Reactor Thermoelectric Space Power, Atomics International, NAA-SR-MEMO-9839 Progress Summary, April 1964

Osmun, W. G., "Space Nuclear Power: SNAP-50/SPUR," Space/Aeronautics, December 1964

Rocklin, S. R., "Design and Testing of the SNAP-10A Thermoelectric Power Conversion System," Paper presented at Thermoelectric Specialists Conference, May 1966

Gylfe, J. D. and R. E. Wimmer, "Reactor-Thermoelectric Power Systems for Unmanned Satellite Applications," Paper presented at the Intersociety Energy Conversion Engineering Conference, Los Angeles, California, 26-28 September 1966

Rappaport, P., "Solar Cells Today," Paper presented at the Intersociety Energy Conversion Engineering Conference, Los Angeles, California, 26-28 September 1966

Stafford, G. B., "Space Power Subsystem Capabilities," AIAA paper 65-468, 29 July 1965

MISSION:

MISSION DESIGN RISK					
Risk Category	Inputs	RER Exhibit	Operations	Risk: 1st Launch	Risk: 2nd Launch
Schedule	N Number of Spacecraft for Launch		1		
Nonspacecraft Technological Innovations	Backup / I / T / R, rows 1, 2, 3, 4		$1 - (1 - \boxed{1}) \cdots (1 - \boxed{4})$ 2		
Operational Mode Complexity	Mode ______ G. A. R. ______ Command Override Yes/No		3		
Summary $_{MD}$	--	--	$1 - (1 - 1)(1 - 2)$ $\times (1 - 3)$		

MISSION:

SUBSYSTEM DESIGN

Risk Category	Inputs					
Spacecraft Technological Innovations			Backup	I	T	
Structure Propulsion Navigation and Guidance Attitude Stabilization and Control Communications Data Management Electrical Power Descent Systems						
Experiments	n =	W	$\boxed{1}$ OMI_R	$\boxed{2}$ OMI_D	$\boxed{3}$ $\boxed{2}$ / $\boxed{1}$	Risk =
Summary_{SBD}						

AND DEVELOPMENT

		RER Exhibit	Operations	Risk	
				1st Launch	2nd Launch
Risk	1 2 3 4 5		$\text{Risk} = 1 - (1 - \boxed{1})(1 - \boxed{2}) \cdots (1 - \boxed{5})$ ①		
	1 2 3 4 5 6 7 8		$\text{Risk} = 1 - (1 - \boxed{1})(\cdots)(1 - \boxed{8})$ ②		
1 - $\boxed{3}$	$\boxed{4}$ $\boxed{5}$ $\boxed{6}$ $\boxed{7}$ $\boxed{8}$		$R_{EX} = \sum_{i=1}^{i=n} \frac{WR_i}{n}$ ③		
			$R_{SBD} = 1 - (1 - ①)(1 - ②)(1 - ③)$		

MISSION:

COMBINED SYSTE

Risk Categories	Inputs				
Environmental Knowledge (R_{EN})	Level of Knowledge ______				
Sterilization Intensity (R_{SI})	Sterilization Temperature ________ °C				
Subsystem Interaction (R_{SSI})	Percent Total Engr. Effort Devoted to System Testing and Simulation Per Module ____________	Modules	I/M	Risk	$\boxed{1}$ $\boxed{2}$ $\boxed{3}$ $\boxed{4}$
Module Interaction (R_{NI})	Percent of Total Engr. Effort--All Modules Devoted to Module Testing ____________	Number of Modules = ____________________			
Test Plan Risk (R_{TP})		Modules	Prior Test Experience	$\boxed{1}$ TEIR	$\boxed{2}$ TE

Summary

Combined Systems Testing Risk (R_{CST})	______________________		

$R_{CST} = 1 - (1 - R_{EN})(1 - R_S$

$= 1 - (1 - 1)(\cdot\cdot\cdot)(1 -$

MS TESTING RISK

Operations	RER Exhibit	Launch Risk 1st Launch	Launch Risk 2nd Launch
①			
②			
Risk = 1 - (1 - $\boxed{1}$)(· · ·)(1 - $\boxed{4}$) ③			
④			
D | $\boxed{3}$ No. of Flights | $\boxed{4}$ $\boxed{2}$ / $\boxed{1}$ | $\boxed{5}$ Risk = 1 - $\boxed{4}$ | R = 1 - (1 - $\boxed{6}$)(· · ·)(1 - $\boxed{9}$)			
$\boxed{6}$ $\boxed{7}$ $\boxed{8}$ $\boxed{9}$ ⑤			

$)(1 - R_{SSI})(1 - R_{MI})(1 - R_{TP})$

⑤)

81-2

MISSION:

SPACE FLIGHT OPERATIONS RISK

Risk Categories	Inputs	RER Exhibit	Launch Risk	
			1st Launch	2nd Launch
Mission Time (R_{MT})	Mission Time ____ Days Year ____			
Changes of State (R_{CS})	Number of Changes of State ____ Number of Spacecraft Per Launch ____			

Summary

Space Flight Operations Risk (R_{SFO})				

$$R_{SFO} = 1 - (1 - R_{MT})(1 - R_{CS})$$

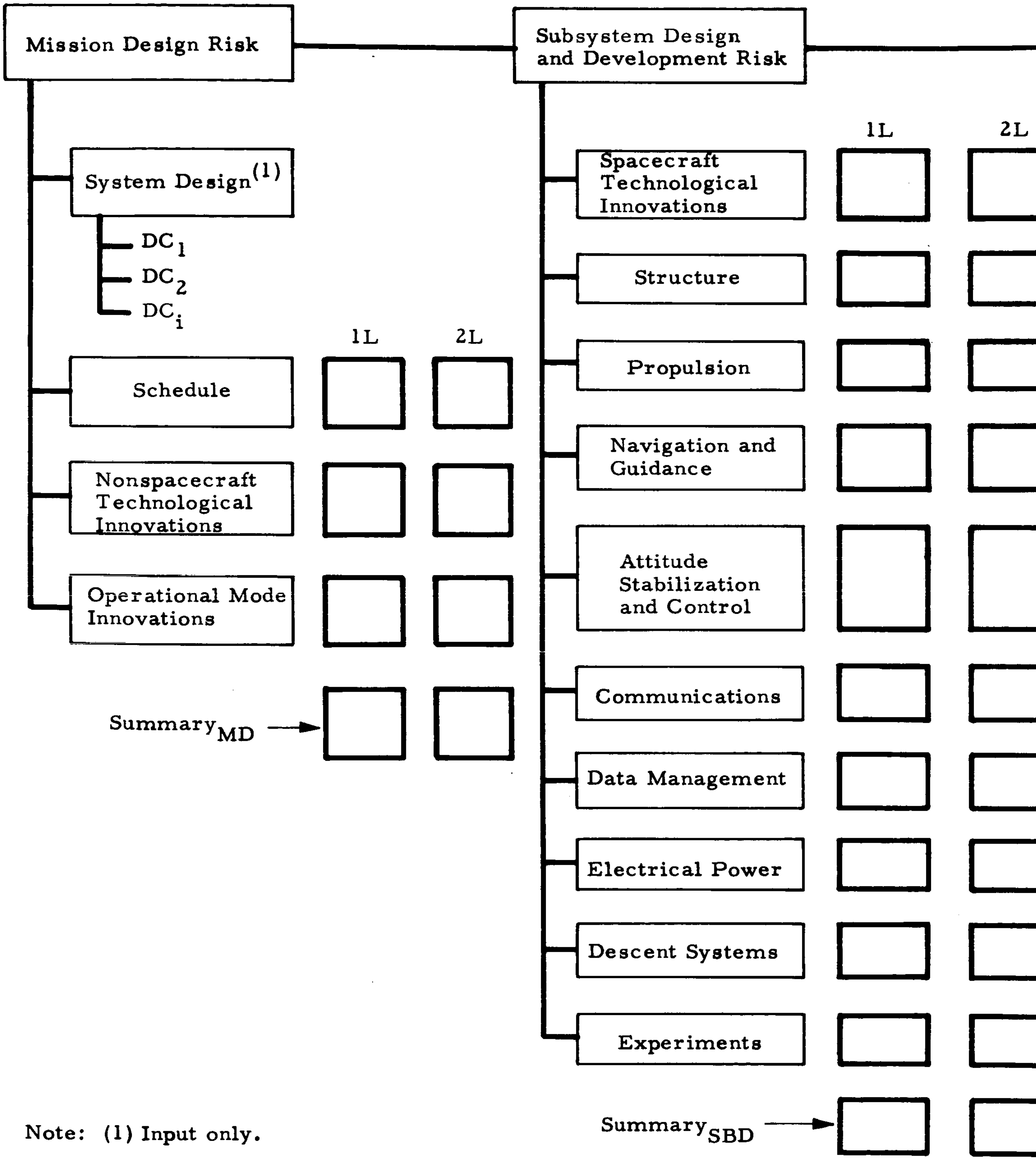
Mission Risk Summary (R_P)

Risk Categories	Launch Risk	
	1st Launch	2nd Launch
Mission Design (R_{MD})		
Subsystem Design and Development (R_{SBD})		
Combined Systems Testing (R_{CST})		
Space Flight Operations (R_{SFO})		

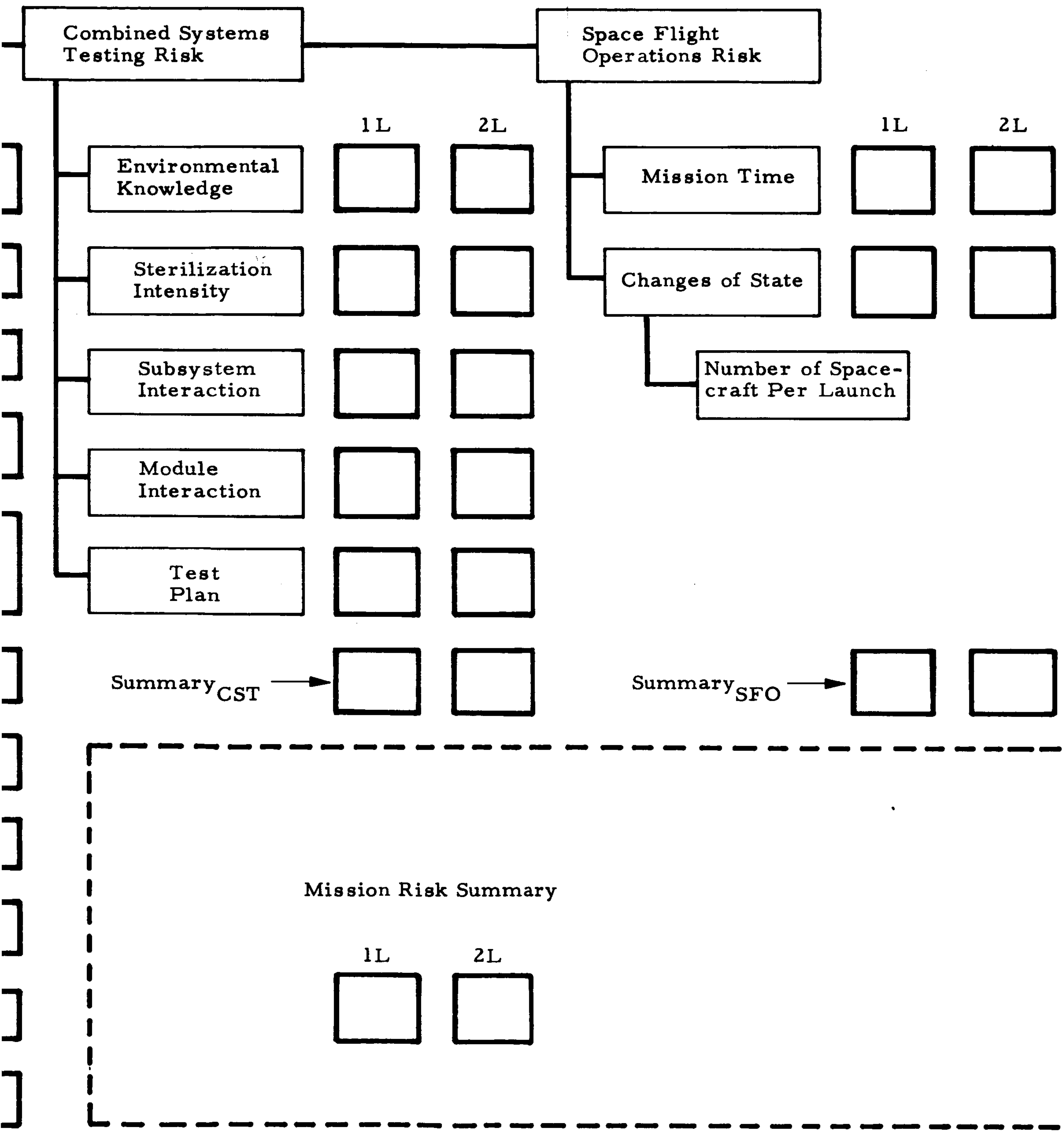
Mission Risk Summary (R_P)		

$$R_P = 1 - (1 - R_{MD})(1 - R_{SBD})(1 - R_{CST})(1 - R_{SFO})$$

MISSION:



Note: (1) Input only.


Combined Systems Testing Risk
Space Flight Operations Risk
1L
2L
Environmental Knowledge
Sterilization Intensity
Subsystem Interaction
Module Interaction
Test Plan
Summary$_{CST}$
1L
2L
Mission Time
Changes of State
Number of Spacecraft Per Launch
Summary$_{SFO}$
Mission Risk Summary
1L
2L